Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
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Balsi Beam Deployment Support

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16. Abstract

This study deals with a cost benefit analysis of the Balsi Beam Crash protection System. This system has been developed by the California Department of Transportation (Caltrans) to provide positive protection for the highway workers. California highway work zone injury data for a period of 10 years was evaluated to understand the relevant parameter sin highway work zone accidents. A statistical analysis of this data was performed and showed that five parameters (Work Activity Type, Time of Day, Work Zone Duration, Vehicle Miles of Travel of the area, and the Location or Type of Roadway) have the most significant effect on injury severity. An Injury Risk Index is then defined to capture the composite effects of all these five parameters in a single metric for use in risk assessment and cost benefit analysis. The study then develops a cost model and combines it with the Risk Index to evaluate the risk mitigation and averted injury cost benefits achieved by the use of the Balsi Beam Barrier system at appropriate work zones. The study also develops methods for evaluating additional operational costs of the Balsi Beam Barrier system but since these costs are found to be dependent on site specific information they only sample calculations are provided. Although the methods developed in this study provide a basis for cost benefit analysis and risk assessment of the Balsi Beam Barrier as well as other Barrier systems, the specific data on actual injury cost averted should be used very carefully due to the limited nature of the data set and the fact that some unfortunate fatalities existed in the data set increasing the overall averted cost of injuries.

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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration, or the University of California. This report does not constitute a standard, specification, or regulation.

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Chapter 1

Introduction

1.1 Project Overview

The Balsi Beam Crash Protection System has been developed by the California Department of Transportation (Caltrans) to provide positive protection for the highway workers working adjacent to on-going traffic in highway work zones. The system was developed as a mobile work zone protection device to protect Caltrans employees working on highway pavements during highway maintenance operations. It was originally designed by Ms. Angela Wheeler of the Division of Maintenance using research data from Mr. Gary Gauthier of the Division of Research and Innovation.

The Balsi Beam is an innovative concept that allows for rapid deployment of a guardrail type device to provide positive protection for workers within a lane closure. One unit of this system is in use as a form of on-site evaluation. Limited crash testing was performed on the system demonstrating its effectiveness. There was, however, a need for further studies evaluating this system and understanding its safety potential, as well as work zone types that would fully benefit from these safety improvements. In particular, there is a need for a proper risk assessment and safety benefit analysis study for this innovative concept.

The purpose of this work is to perform such an analysis of risks and the potential safety benefits of the Balsi Beam system for working and mobility safety enhancements and improvements. The scope of the work is limited to a paper study involving development of quantitative and qualitative models for such an assessment and a cost benefit analysis. The aim is to develop injury cost models for work zone safety evaluation, and to develop an understanding and prioritization of highway maintenance projects that would receive the most benefit from the Balsi Beam system.

1.2 Task Summary and Approach

Any analysis of safety benefits derived from a crash protection device requires an understanding of crash types and primary injury mechanisms in the type of environment for which the device is designed for, as well as exposure data that would allow determination of crash rates. This information then needs to be combined with injury cost models and statistical evaluation to perform a risk assessment and cost benefit analysis.

In the case of the Balsi Beam, two types of analysis are needed to identify crash types. One is to perform an epidemiological type study of previous work zone type accidents using available databases. The second is to perform an analysis of collision types using predictive models and the existing design of the Balsi Beam system to identify collision angles, workspace boundary movements, and intrusion potentials for the system.

Identification of crash types is an important step in an analysis of risks and benefit derived from any crash protection device. It has been used for seat belts, [6, 21], for head restraints, [25], and for a variety of other automotive related crash protection devices,[14]. A similar type study is needed for work zone accidents. This was performed in Task 1 of this research, where California work zone injury data were evaluated.

Task 2 of this research involved developing injury evaluation criteria for work zones. Development of such criteria is important for proper cost benefit analysis as well as risk assessment. The approach performed here evaluated trends in injury occurrence and severity in highway work zones, using logistic and Poisson regression models. This also involved defining an index to measure the risk of injury, or exposure, a worker experiences in a highway work zone.

The next step in the research involved development of injury cost models for work zone injuries. This was performed under Task 3. Developing injury cost models is an important step in cost benefit analysis of any crash protection device or system. One has to consider both direction economic costs to as well as the total economic cost. These costs cover direct losses and economic costs of motor vehicle crashes as well as the economic value society places on the human life and pain and suffering. In the case of motor vehicle accidents, previous studies have standardized such an evaluation, [4, 17, 33] for the National Highway Traffic Safety Administration (NHTSA) by defining cost estimate criterion. This research used the most updated cost estimate guideline proposed by the Federal Highway Administration (FHWA) as the value of a statistical life (VSL).

Finally, Task 4 was completed, in which a safety benefit analysis was developed, combining the results of the previous tasks. The injury cost model was combined with operational costs to fully evaluate the benefits of Balsi Beam deployment.

Task 5 is completed in this report, as a set of recommendations and guidelines are presented which summarize the results of the study.

1.3 Task List

1. Analyze Crash Data From Work Zone Accidents
    (a) Identify crash types
    (b) Identify primary injury mechanisms
    (c) Identify trends in injury occurrence and severity
2. Develop Injury Risk Evaluation Criteria

    (a) Evaluate work zone injury data
    (b) Develop a method to measure/quantify risk of injury
3. Develop Injury Cost Model
    (a) Identify cost estimates for injuries
    (b) Evaluate costs of evaluated injuries
4. Perform Safety Benefit Analysis
    (a) Perform cost benefit analysis using injury cost model and operational cost estimates
    (b) Perform risk assessment combining injury evaluation and cost benefit analysis
5. Develop Recommendations
    (a) Develop guidelines that can be used for decision making on prioritization for deployment of Balsi Beam for various roadway work zones.
6. Documentation and Reporting

Chapter 2

Analysis of California Work Zone Injury Data

2.1 Introduction

The importance of work zone safety and risk assessment is evident. However, the means of measuring risk in the highway work zone has not been established. The term *work zone exposure* is a commonly used term to quantify exposure to risk of serious and/or fatal injury. Ullman et al.[27], evaluated work zone exposure measures after noting that comprehensive data do not exist on work zone exposure characteristics. Ullman et al. evaluated various work zone exposure measures, including the length, duration and frequency of work zone activity, impact of work zone on available roadway capacity, vehicle exposure to both active and inactive work zones, and the percent of the highway system with at least one day of work zone activity. The purpose of this study was to evaluate the quality and quantity of work zone data in the United States. The most frequent use of *work zone exposure* measures, in research, has been in the study of work zone accidents, and the effect of the work zone on vehicle collisions, focusing, primarily, on the traveling public. Khattak et al.[15], evaluated the effect of the presence of a work zone on injury and non-injury crashes in California. In a similar study, Schrock et al.[23], thoroughly evaluated 77 fatal work zone collisions, in order to develop possible countermeasures to improve work zone safety.

In California, in 2004, there were 109 work zone fatalities, 2 of those were workers working in the work zone [8, 18] (Figure 2.1). While worker fatalities are low despite the high exposure, according to the California Strategic Highway Safety Implementation Plan, '*No worker fatalities in work zones is a reasonable goal*' [9]. However, while some research has been done to evaluate the relationships between various work zone characteristics and the rate of accidents, very little has been done focusing on the risk of injury to the worker.

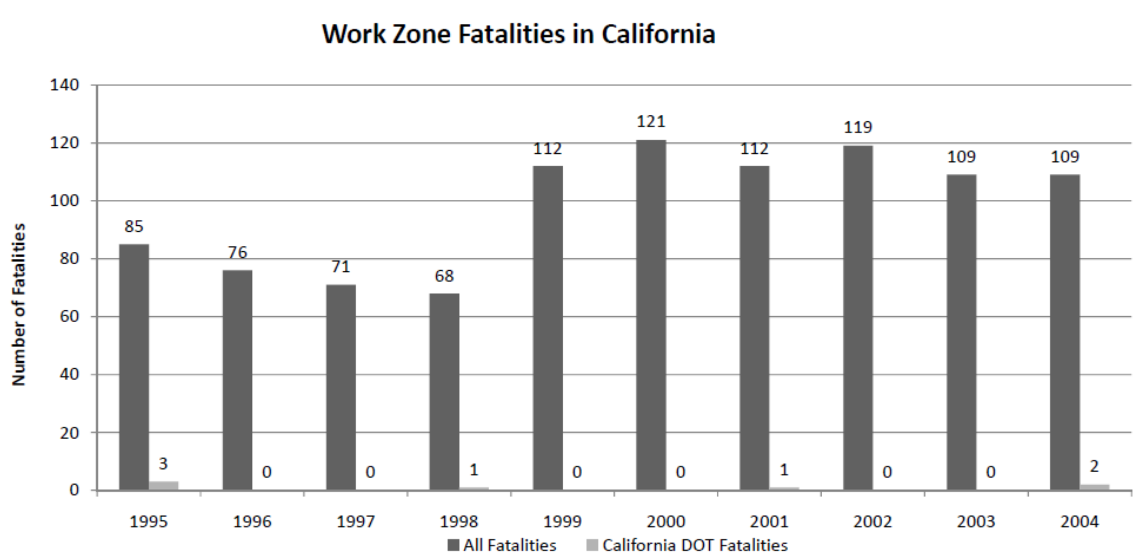


Figure 2.1: Number of fatalities in California work zones. The larger tally represents all fatalities cause by motor vehicle accidents in and around construction and maintenance zones, where the smaller corresponds to Caltrans employees working in the work zone.

This portion of the research will accomplish the goal of evaluating work zone parameters and how they relate to the risk of injury or fatality for the workers in the work zone. (In the remainder of this research, all injuries considered will be referred to as work zone injury, and they consider only the injuries obtained by the workers in the work zone.) The method for calculation of work zone exposure performed in this research uses the results of work zone injury analysis. Work zone injury data were evaluated to determine evident trends in injuries, and relation to various work zone parameters.

The injury data were evaluated, and the severity of the injury was categorized using the Abbreviated Injury Scale (AIS) [2]. The AIS is an anatomically based, consensus derived global severity scoring system, which classifies an injury in a body region according to its relative importance on a six point scale, [12]. The scale divides the human body into nine regions or groups. These body regions include the head (cranium and brain), face (including eye and ear), neck, thorax, abdomen and pelvic contents, spine (cervical, thoracic, lumbar), upper extremity, lower extremity (including pelvis and buttocks), and external (skin), thermal injuries and other trauma. The injury description defined by AIS assigns a number to each injury, characterizing the severity of the injury. The classes of injury severity are (1) minor, (2) moderate, (3) serious, (4) severe, (5) critical, and (6) maximum injury (currently untreatable).

In addition to the AIS, a second method was used to evaluate the injuries that occurred in the work zone. In many serious accidents the victim is likely to sustain more than one serious injury. The Injury Severity Score, (ISS), is an anatomical scoring system that provides an overall injury score for persons with multiple injuries [3, 13], and is defined as the sum of the squares of the highest AIS grade in each of the three most severely injured body regions. The ISS will be a number in the range of 0 to 75, with any injury assigned an AIS of 6, automatically receiving and ISS of 75. Baker et al.[3], found that persons with an ISS of 10, or less, had high survival rates, where those with an ISS of 50 or greater where much more likely to die as a result of their injuries. Because of its ability to summarize injury severity and good correlation with survival, the Injury Severity Score, is the preferred way to compare both injury severity and rate in different situations.

The object of the work zone injury analysis was two-fold. Evaluation of injury data was performed first to understand the patterns of work zone injuries, and the statistical effects of work zone parameters on the severity of injury. Secondly, using this information, the development of a measure of risk is desired. There are a number of measures used to identify risk, particularly risk to injury in motor vehicle collisions. The metric developed in here, the ‘Risk Index’, was created as a method to effectively measure risk of injury in a work zone. The index calculates an estimate of the risk of serious or fatal injury in a work zone, which can then be compared between numerous work zones. A ‘Risk Index’ of this type would be beneficial to work zone protection planning.

This approach has been applied to measure various parameters in other situations, particularly in studies of occupant safety. Viano et al.[32] developed an index, ‘Motion Criteria’, that considered a number of properties used to determine the relative quality of a lap belt restraint function. By evaluating the ‘Motion Criteria’ in different situations or crash tests, the restraint function was compared at each different setting. The advantage of an index such as the ‘Motion Criteria’ is that comparisons can be readily made between seemingly different situations. Viano et al. used the Motion Criteria measure to relate the level of occupant motion, or lap belt restraint, with the probability of abdominal injury.

Analysis of the California work zone injury data began with an epidemiological evaluation of all reported injuries using Microsoft Access and Excel. Following the evaluation, a detailed statistical analysis was performed for those injuries occurring in the work zone in the ten year period from 1998 through 2007. The statistical software package SAS® (SAS Institute, Inc.) was used to perform regression analysis relating injury and accident parameters with the probability and severity of injury.

2.2 Description of Data

California work zone injury data were analyzed to determine injury trends in highway maintenance work zones. The database from which the data were extracted is a collection of accident and injury reports maintained by the California Department of Transportation. These reports included both vehicle accident reports and personal injury accident reports. Overall, the database contained 36,379 injury reports covering the entire state of California, and providing data from the early 1960s through 2007.

During evaluation, the data fields contained in the database were divided into three categories: accident information, work zone information, and injury information. The accident parameters included the date and time of day of the accident (further categorized into peak/rush hours (07000900, 1600–1900) or non-peak hours), the weather, roadway and visibility conditions at the time of the accident, the location of the accident, the approximate speed limit at the location, the type of accident (classified as either a motor vehicle collision, struck by object, or struck by motor vehicle), the angle of the work zone intrusion (head on, rear end, sideswipe, or broadside), and the estimated vehicle miles of travel (VMT) for the geographic area where the accident took place. The VMT variable was established using estimates of vehicle miles that motorists traveled on California State Highways in the area of the injury, averaging the yearly estimate from 1999 through 2006. The averages were divided into three categories, low, medium and high, based on the geographic area.

Work zone information included the type of maintenance activity being performed by the worker at the time of the accident, the duration of the work activity (categorized as short-term stationary, short duration, or mobile), and whether or not the victim was wearing personal protective equipment (PPE). The Texas Transportation Institute, [26, 30], defined work zone durations based on the time the workers are occupying the area, as shown in Table 2.1. Since this research only focused on short-term and temporary work zones, the duration category only has three levels, short duration, short-term stationary, and mobile.

Work Zone Duration	Description
Long-term stationary	Occupy a location for more than three days
Intermediate term stationary	Occupy a location for more than one daylight period, but no more than three days, or at a night location for at least one hour
Short-term stationary	Occupy a location for one hour or more during a single daylight period
Short duration	Occupy a location for up to one hour
Mobile	Move intermittently or continuously along a roadway segment

Table 2.1: Description of defined work zone durations.

Finally, the injury information incorporated whether or not the incident was fatal, the body region injured, the nature of injury, injury severity (based on AIS and ISS), and the number of lost and modified work days of the victim following the accident. Recall, that ISS is calculated as the sum of the squares of the three most severely injured body regions, which are defined as AIS 1, AIS 2 and AIS 3. A detailed description of the data is shown in Tables 2.2, 2.3 and 2.4.

2.3 Epidemiology of Work Zone Injury Data

Methods

An epidemiological analysis of the Caltrans accident data was carried out in a number of steps. The purpose of this analysis was to identify trends in the injury data, specifically related to Location, Accident Type, VMT, and Activity Type parameters. The entire data set was first evaluated by dividing Accident Type and looking at various accident, work zone and injury parameters including Location of Accident, Activity Type, Lost/Modified Time, Fatal Accident, and VMT. Each succeeding analysis evaluated a smaller subset of injury data.

Variable	Class Level	Variable Type
Time of Day	Non-peak Hour Peak/rush Hour	Class variable
Weather	Dry/clear Snow/wet	Class variable
Visibility	>1/2mile <1/2mile	Class variable
Location	City Street Freeway/Highway Freeway Lane Closure Freeway Ramp Moving Lane Closure Shoulder Closure	Class variable
Speed Limit		Continuous

Type of Accident	Motor Vehicle Collision Struck by Motor Vehicle Struck by Object	Class variable
Angle of Intrusion	Head On Rear End Sideswipe Broadside	Class Variable
Vehicle Miles of Travel	Low Medium High	

Table 2.2: Detailed description of accident variables used in analysis of California work zone data.

Variable	Class Level	Variable Type
Activity Type	Driving On Foot	Class variable
Duration	Short-term Stationary Short Duration Mobile	Class variable
PPE	True False	Class variable

Table 2.3: Detailed description of work zone variables used in analysis of California work zone data.

Variable	Class Level	Variable Type
Fatal	True False	Class variable
Body Region	Head Face Neck Thorax Abdomen Spine Upper Extremity Lower Extremity Whole Body/Multiple	Class Variable

Nature of Injury	Abrasion Amputation Bone Fracture Bruise Concussion Crush/Pinch/Cut/Puncture Cumulative Trauma/ Multiple Dislocation Death by Injury Soreness Strain/Sprain Torn Muscle	Class variable
AIS 1	1–6	Class variable
AIS 2	1–6	Class variable
AIS 3	1–6	Class variable
ISS		Continuous
Modified Days		Continuous
Lost Days		Continuous

Table 2.4: Detailed description of injury variables used in analysis of California work zone data.

The next step in the accident evaluation was to assess only the reports in which the Accident Type field was either motor vehicle collision, struck by object, or struck by motor vehicle. Data where evaluated, focusing on work zone accidents, including both work zone intrusions and accidents occurring within the work zone. This level of evaluation examined the work zone accidents by Month of accident, Time of Day, and the VMT where the incident took place.

The final level of epidemiological analysis focused on only work zone intrusion data. The data were evaluated based on the type of work zone Intrusion Angle, Body Region of injury, injury severity (measured by AIS and ISS), Maintenance Activity, Visibility, Nature of Injury, number of Modified or Lost Work Days, Weather Conditions, PPE usage, Preventability, and Class Title of Victim. Graphics for each analysis were prepared in Excel, and will be further discussed.

Results

The results of the epidemiological evaluation of the injury data are shown in Table 2.5 through Table 2.10, and Figure 2.3 through Figure 2.13. As described, the analysis started by looking at the general trends of accident reports from the entire dataset. Each step of observations narrowed the analysis until the final analysis only involved incidents which were reported as work zone intrusion accidents.

Table 2.5 below shows the first level of analysis of the overall accident trends, looking at the Accident Type versus Location of Accident. Of the motor vehicle collisions, the top three locations were freeway/highway, City Street and freeway ramp, respectively. Similarly, freeway/highway was the most frequent site for struck by motor vehicle accidents, with all other locations averaging around thirteen accidents. The struck by object accident type category has the largest number of accidents occurring in none roadway locations. The locations, included in the 'non-roadway' category were cafeteria/restaurant, common carrier, crew's quarters, elevator, equipment bay, laboratory, maintenance yard, office building, parking lot, residence, rest area, shop/warehouse, stairway, and unknown (not reported) locations. The 'other*' category of the Accident Type variable was created to encompass those accident types which were not considered to occur in a work zone, or would not be caused by a work zone intrusion. These accidents incorporated: altercation with other, animal/insect bite/sting, repetitive body motion, single event body motion, caught in machinery, caught in non-machinery, chemical exposure, contact with electrical current, contact with flame/fire, contact with hot object, contact with poisonous plant, contact with sharp object, exposure to hazardous material, exposure to dust, exposure to gas/fumes, exposure to high/low temperatures, exposure to infectious material, exposure to irritants, exposure to loud noises, exposure to sun, exposure to virus, fall from ladder/steps, fall from spilled liquid, foreign object in eye, radiation exposure, stress and trip/slip/fall.

	MV Collision	Struck by MV	Struck by Object	Other*
City Street	479	18	91	739
Construction Site	35	18	102	1175
Freeway Lane Closure	35	26	65	513
Freeway Ramp	142	28	196	1668
Freeway / Highway	1331	121	975	10169
Hwy Structure / Bridge	54	13	184	1897
Moving Lane Closure	41	2	2	57
Shoulder Closure	21	15	126	1066
Street / Hwy Lane Closure	26	7	42	414
Sidewalk	1	0	11	171
Tunnel / Tube	0	0	4	97
Non-Roadway	67	18	1284	13707

Table 2.5: Evaluation of Caltrans injury data by Accident Type and Location of accident. (MV: Motor Vehicle)

The second general analysis of the injury data evaluated the frequency of an Accident Type when taking into account the Activity Type, and is shown in Table 2.6. The most frequent activity type in motor vehicle collision accidents was driving, riding or sitting. For struck by motor vehicle accidents, the most frequent activity is walking, followed closely by standing. The most common work activity being performed during a struck by object incident is the combination of lifting, carrying, pulling, pushing and reaching, and the second most common known activity is using a hand tool. A large portion of the activities in the struck by object incidents were unknown, or classified as not relevant to this analysis. The activity types deemed not relevant include adverse action, altercation with co-worker or supervisor, burning, disciplinary action, enter/leave vehicle, office work, using bench tools, using shop machinery, or unauthorized activity. In further analysis, the Activity Type variable was divided into two categories, driving, or on foot. The activities that were included in the driving level were driving, riding, sitting, and enter/leave vehicle. The on foot level incorporated assigned duties, flagging, inspecting, standing, bending, stooping, shoveling, using hand tools, walking, jumping, running, diving, lifting, carrying, and reaching.

The next overall evaluation assessed the number of Modified and Lost Days required following incidents based on the accident type. Referring to Table 2.7, the majority of reported accidents in all four categories of accident type required less than five days of lost or modified time. The Accident Type requiring the most lost and/or modified time was the struck by motor vehicle category, indicating that these accidents produce more serious injuries. This conclusion in backed up by Table 2.8, in which the number of fatal accidents by Accident Type is shown.

	MV Collision	Struck by MV	Struck by Object	Other*
Flagging	1	12	5	120
Gardening	1	4	44	657
Inspecting	5	24	84	803
Lifting, Carrying, Pulling, Pushing, Reaching	9	12	1012	8322
Running	4	4	8	194
Shoveling	2	10	26	677
Sitting, Riding, Driving	2092	17	102	1453
Standing	14	58	250	847
Stooping, Bending, Climbing	1	7	145	2358
Using Hand Tool	2	9	513	2754
Walking	4	66	26	3814
Unknown, Not Relevant	97	43	867	9674

Table 2.6: Breakdown of injury data by reported Activity Type. (MV: Motor Vehicle)

Modified Time

Days	MV Collision	Struck by MV	Struck by Object	Other*
0	68.69	65.46	69.23	67.43
1–5	11.44	14.06	14.74	12.37
6–10	8.11	5.62	7.72	8.59
11–20	3.78	2.81	4.51	4.77

21–30	2.84	2.01	1.56	2.41
31–40	0.77	2.01	0.52	0.91
41–100	3.78	5.22	1.53	2.97
Over 100	0.59	2.81	0.19	0.54

Lost Time

Days	MV Collision	Struck by MV	Struck by Object	Other*
0	70.18	51.41	84.71	78.80
1–5	15.90	13.25	9.15	10.40
6–10	3.11	4.42	1.40	2.48
11–20	2.16	5.62	1.27	2.02
21–30	1.58	2.41	0.88	1.38
31–40	0.77	3.21	0.39	0.71
41–100	2.25	4.42	1.27	2.17
Over 100	4.05	15.26	0.94	2.02

Table 2.7: Percent of Modified and Lost Days by Accident Type. (MV: Motor Vehicle)

	MV Collision	Struck by MV	Struck by Object	Other*
Fatal Accidents	12	17	1	27

Table 2.8: Fatal accidents by Accident Type. (MV: Motor Vehicle)

The final general analysis of the complete accident dataset evaluated the Accident Type by the VMT or Vehicle Miles of Travel of the geographic area in which the accident occurred. Of the roadway accidents, the highest percentage of motor vehicle collision and struck by motor vehicle accidents occurred in areas of high VMT, and the highest percentage of struck by object accidents occurred in areas defined as low VMT regions, as shown in Table 2.9. The occurrence of accidents in high and low VMT regions was higher than in areas categorized as having medium VMT levels. While the large quantity of accidents in low VMT areas is unsettling at first, it can be explained by Figure 2.2, which shows the number of California districts in each VMT category. Eight of twelve districts of California are grouped into the 'Low' category based on the division of the VMT range.

	MV Collision		Struck by MV		Struck by Object		Other*	
	#	(%)	#	(%)	#	(%)	#	(%)
Low	805	(36.07)	94	(35.34)	1337	(43.38)	13792	(43.54)
Medium	295	(13.22)	43	(16.17)	393	(12.75)	3892	(12.29)
High	975	(43.68)	113	(42.48)	1173	(38.06)	11672	(36.85)
Unknown	157	(7.03)	16	(6.02)	179	(5.81)	2317	(7.32)

Table 2.9: Spread of injury accidents types throughout the districts of California. (MV: Motor Vehicle)

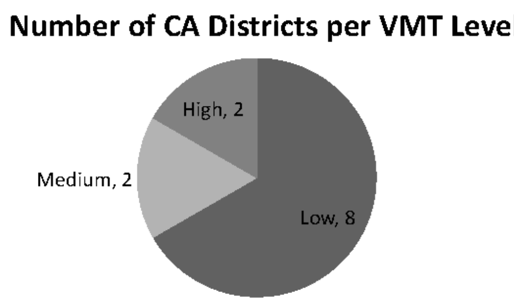


Figure 2.2: Division of California Department of Transportation Districts into Vehicle Miles of Travel (VMT) categories.

The second level of evaluation narrowed the accident data down to accidents that were reported as either motor vehicle collision, struck by motor vehicle, or struck by object. Table 2.10 shows the percent of work zone intrusion and within work zone accidents for each Accident Type. The table shows that 15% of all motor vehicle collisions were work zone intrusions, and only about 3% occurred within the work zone. A total of 80% of the struck by motor vehicle accidents occurred in the work zone, about 50% as work zone intrusions with the remaining 30% occurring within the work zone. Only approximately 1% of the struck by object accidents were a result of a work zone intrusion, but 41% occurred within the work zone. Figure 2.3 shows percentage of the Accident Type of interest for work zone intrusion accidents and within work zone accident types. The majority of the work zone intrusion accidents were classified as motor vehicle collision (68%), followed by struck by motor vehicle (26%), and struck by object incidents (6%). The frequency of accident types of within work zone accidents differed from work zone intrusions, with the majority (88%) classified as struck by object, and the remaining divided equally between motor vehicle collisions (6%) and struck by motor vehicle collision (6%).

	MV Collision		Struck by MV		Struck by Object	
	#	(%)	#	(%)	#	(%)
Work Zone Intrusion	351	(15.41)	132	(49.07)	32	(1.04)
Within Work Zone	83	(3.64)	84	(31.23)	1265	(41.03)

Table 2.10 Work zone accidents broken down by Accident Type. (MV: Motor Vehicle)

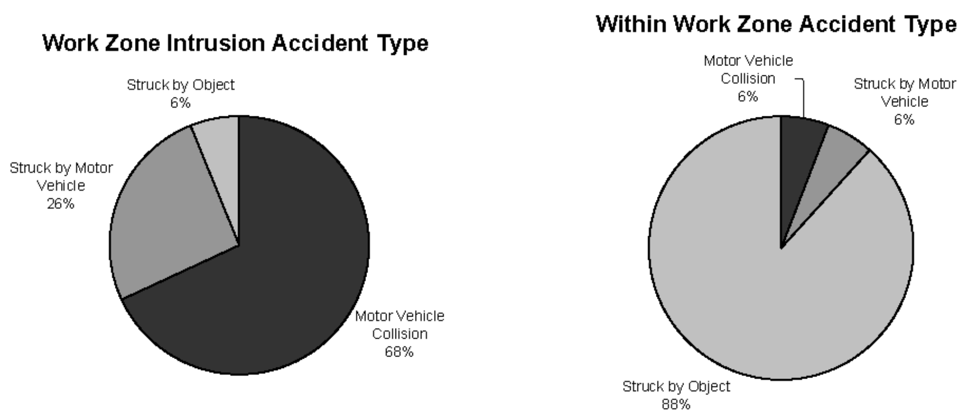


Figure 2.3: Work zone accidents divided by Accident Type.

Figure 2.4 and Figure 2.5 shows the breakdown of work zone accidents (work zone intrusion and within work zone accidents) by month and time of day. The average number of work zone intrusion accidents was calculated to be 42.92 ± 6.88, compared to the mean number of within work zone incidents, 119.33 ± 17.46. While there is some difference in the number of accidents from month to month in Figure 2.4, the standard deviation is not large. However, there is a large variance across reported time of day graphic. For work zone intrusion accidents, the average number of accidents was found to be 20.38 ± 23.53, and for within work zone accidents the mean was 53.13 ± 74.77. In both cases, the standard deviation is larger than the mean.

The evaluation of work zone incidents based on VMT is shown in Figure 2.6. The graphic shows the highest number of work zone intrusion accidents occurred in areas with high vehicle miles of travel, or heavy traffic. However, the highest number of within work zone accidents occurred in areas of low VMT.

The final step in epidemiological analysis dealt with work zone intrusion accidents only. Figure 2.7 below shows the reported intrusion angle for all work zone intrusion incidents. The most common intrusion angle is entrance from the rear of the work zone, or a rear end intrusion. Figure 2.8 illustrates the injury break down of the reported accidents. These graphics show that the majority of the injuries are considered minor, and the highest percentage of injuries were back injuries. The injury analysis agrees with Figure 2.9, which shows the number of modified and lost days as a result of the injury. Figure 2.10 shows that in most cases, the roadway conditions were ideal for worker safety: clear, dry roadways. The breakdown of work zone intrusions by maintenance activity is illustrated in Figure 2.11. The letter codes for each maintenance activity correspond to an assigned activity code, as described in Table 2.11.

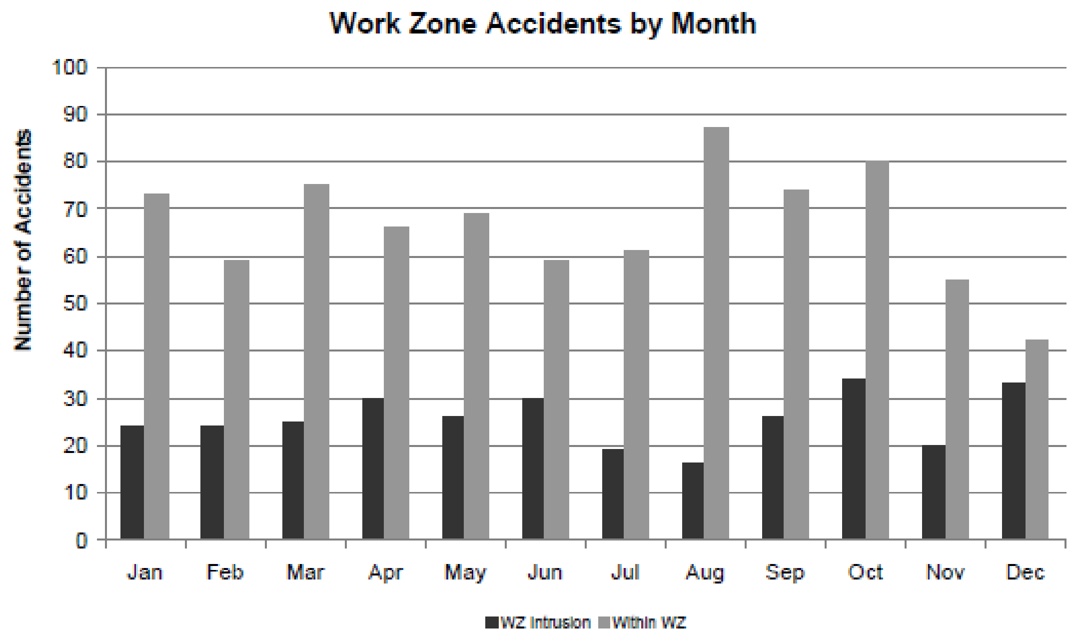


Figure 2.4: Break down of work zone accidents by month.

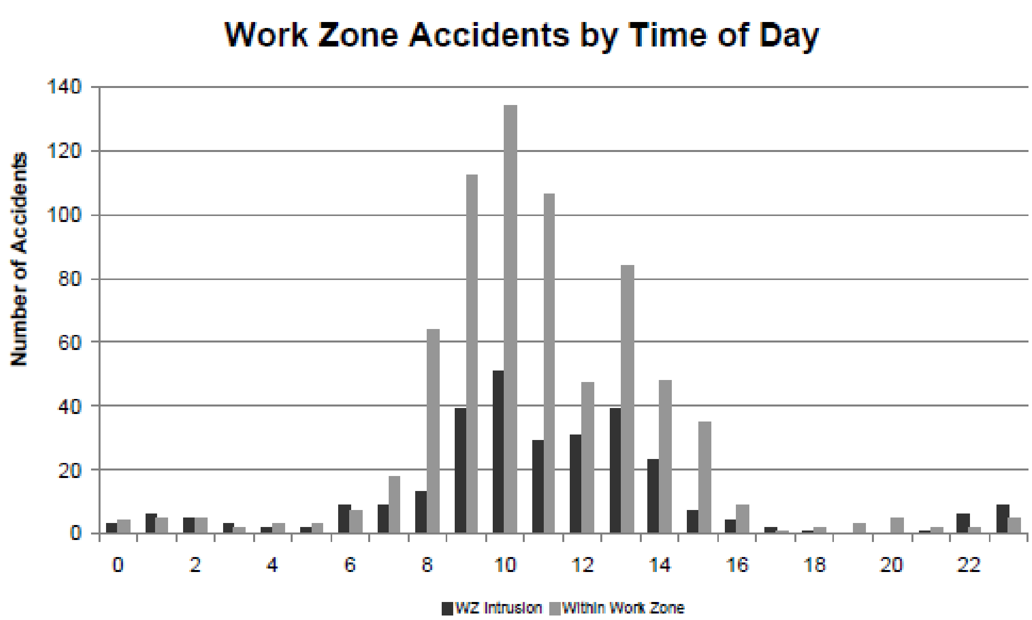


Figure 2.5: Work zone accidents by time of day.

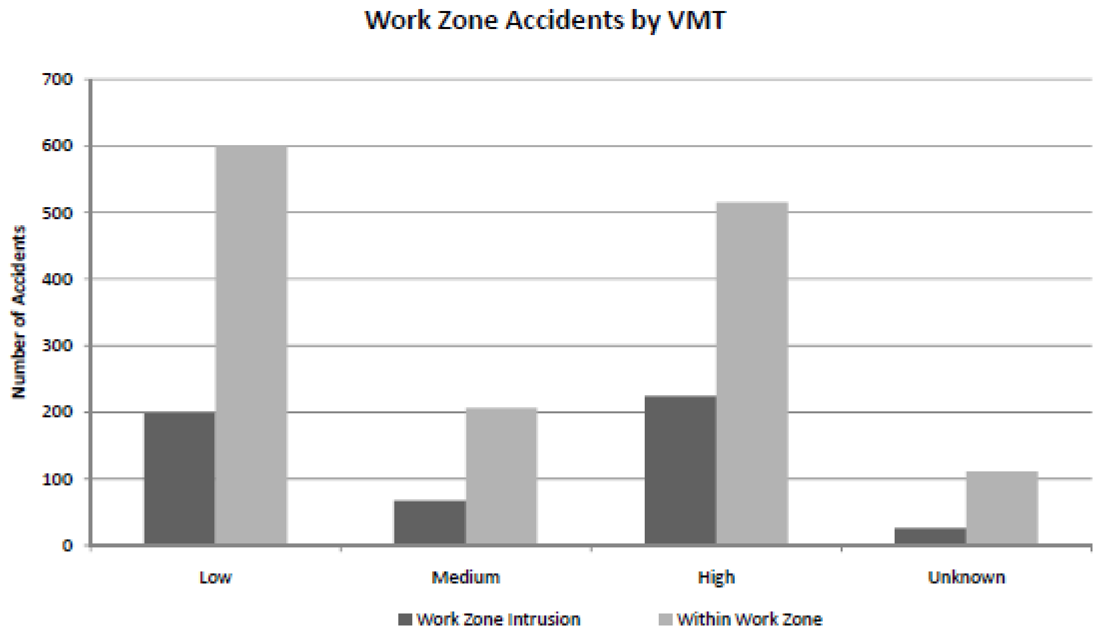


Figure 2.6: Distribution of work zone accidents across Vehicle Miles of Travel (VMT) levels.

A	Flexible Pavement	J	Other Structures
B	Rigid Pavement	K	Electrical
C	Slope/Drainage/Vegetation	M	Traffic Guidance
D	Litter/Debris/Graffiti	R	Snow/Ice Control
E	Landscaping	S	Storm Maintenance
F	Environment	W	Training/Field Auxiliary Services
H	Bridges	Y	Work for Others

Table 2.11: Description of Caltrans maintenance activity codes.

The two most common activities in which a work zone intrusion occurred were Litter/debris and Graffiti cleanup, and traffic guidance work. The second graphic describing the breakdown of work zone intrusions, deals with maintenance activities in a more general way, based on the duration of the work zone, (Figure 2.11). In this analysis, work zones were categorized as one of three defined work zone durations, short-term stationary, short duration, or mobile. A short-term stationary work zone occupies a location for one hour or more during a single day. The most common duration in which a work zone intrusion occurred was a moving work zone. Figure 2.12 shows that the majority of workers were wearing personal protective equipment at the time of the accident, and that over 90% of the incidents were not preventable on the part of the worker, as reported by the on-site supervisor. Finally, Figure 2.13 shows the classification title, or job position of the victim. The first figure shows that the most frequently injured workers are those acting as equipment operators, while the second most frequently injured are highway maintenance workers.

The second figure shows the level or rank of the injured worker. The highest percentage of victims of work zone intrusions includes landscape and maintenance workers. This result is not surprising, as landscape and maintenance workers make up the largest demographic of the work zone work force.

2.4 Statistical Analysis of Work Zone Injury Data

The procedure used in the statistical analysis of the injury data followed the 'Model Building Process' outlined in Kutner et al., [16]. The steps required to build a statistical model are outlined below:

1. Data collection and evaluation using co linearity procedures.
2. Reduction of explanatory or predictor variables using variable stepwise and backward selection methods.
3. Model refinement and selection using goodness of fit and residual evaluation.
4. Model validation by evaluating predictive power statistics.

The statistical analysis was done using the SAS statistical package (SAS Institute Inc.).

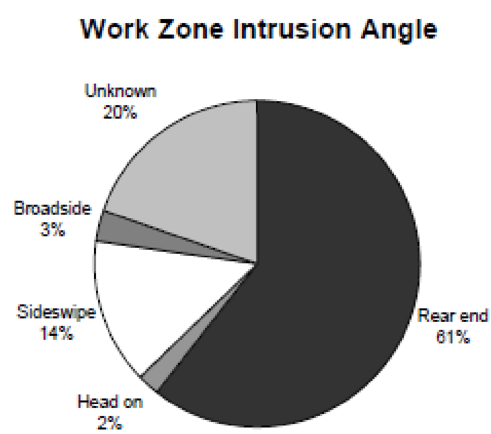


Figure 2.7: Reported intrusion angle of errant vehicles into the work zone.

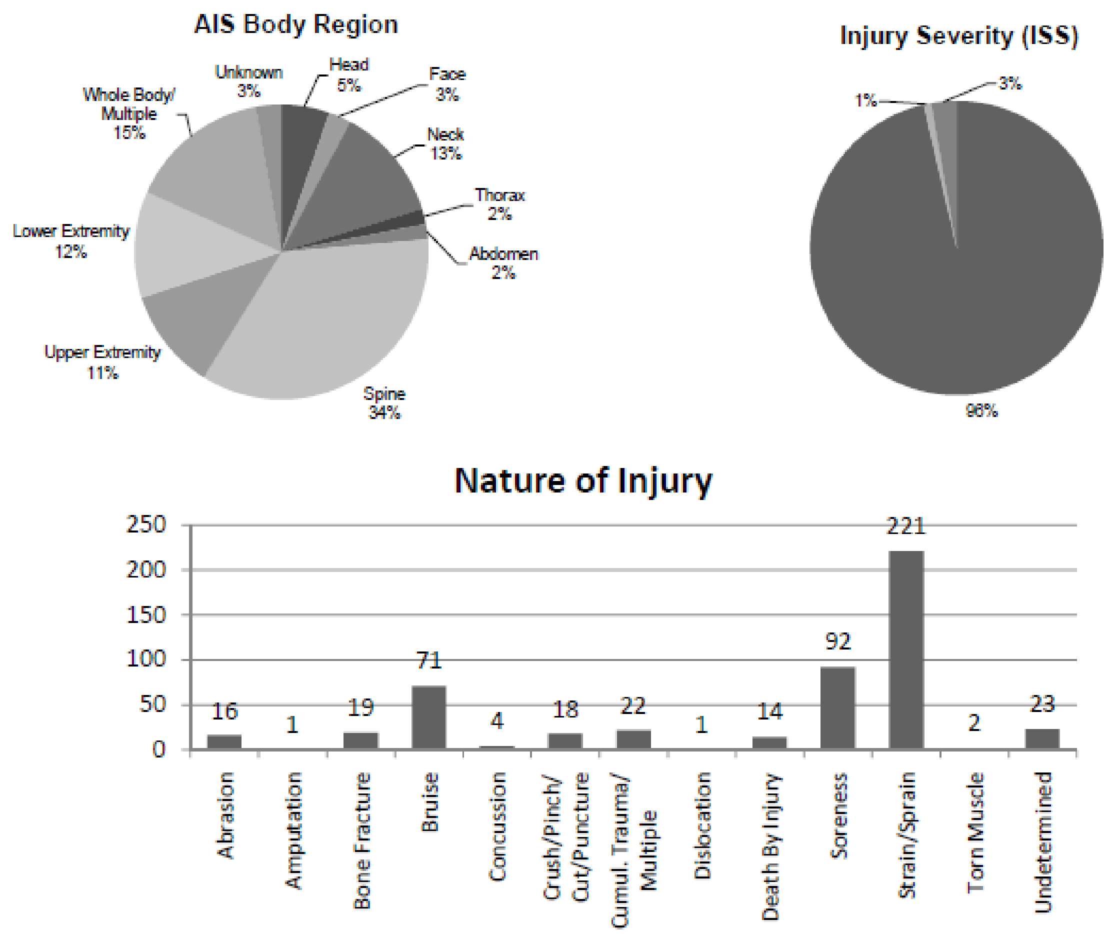


Figure 2.8: Reported body region injured, injury severity, and nature of injury in California work zone injuries due to intrusion of an errant vehicle.

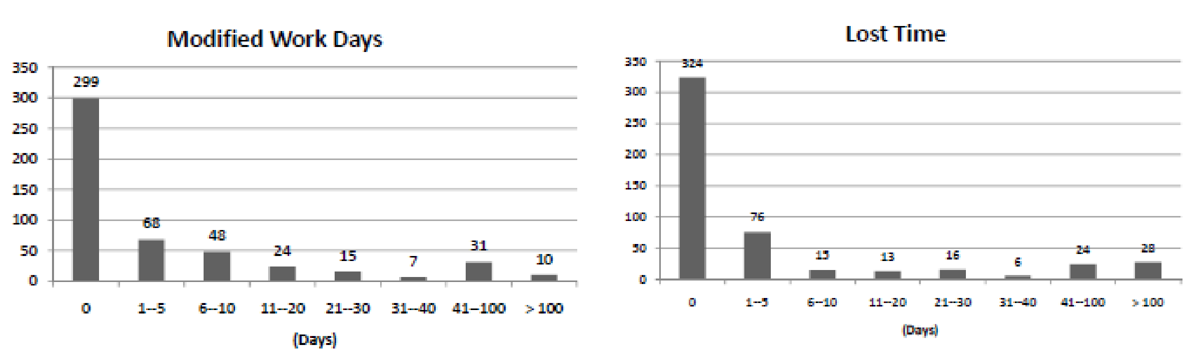


Figure 2.9: Modified and lost time (days) required following injuries in work zone intrusion accidents.

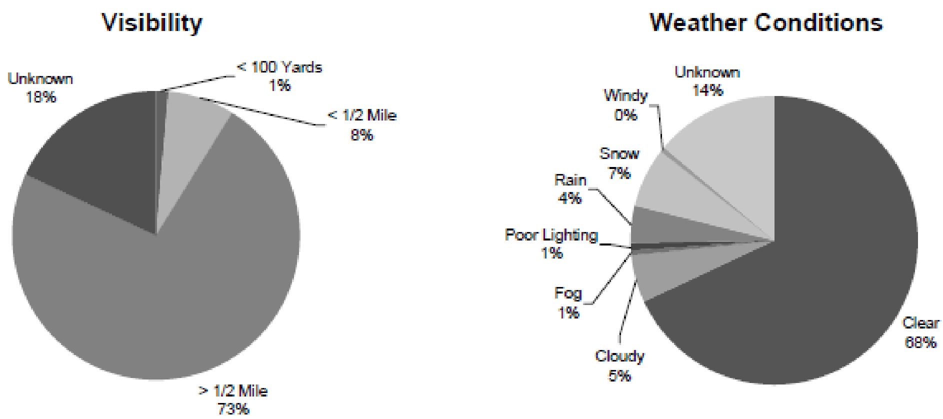


Figure 2.10: Visibility and weather conditions reported at the time of injury in California work zones.

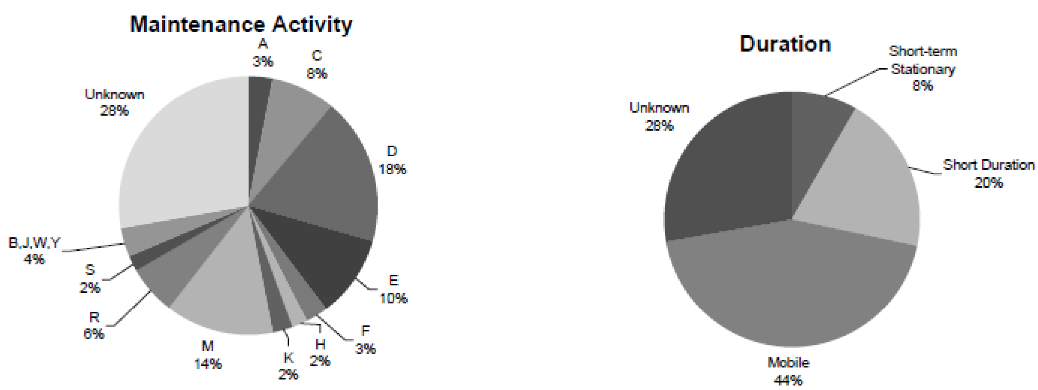


Figure 2.11: Recorded maintenance activity and corresponding duration of work zone at the time of a work zone intrusion.

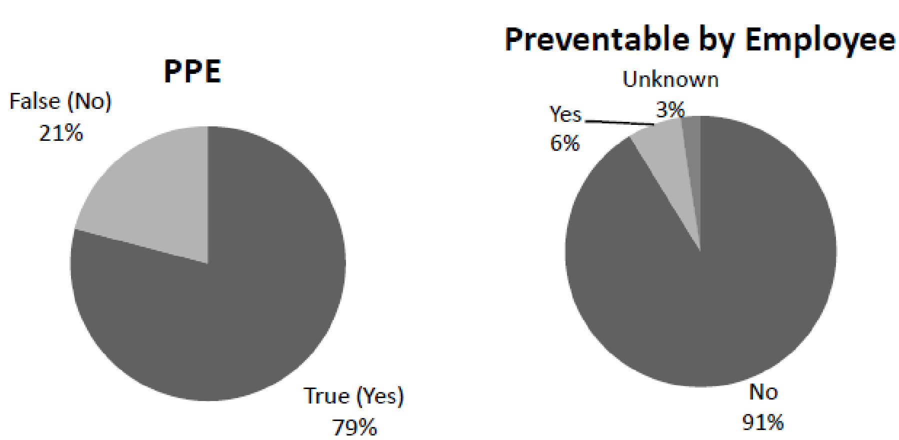


Figure 2.12: PPE usage and whether or not the incident was preventable by the employee, in California work zone injury data.

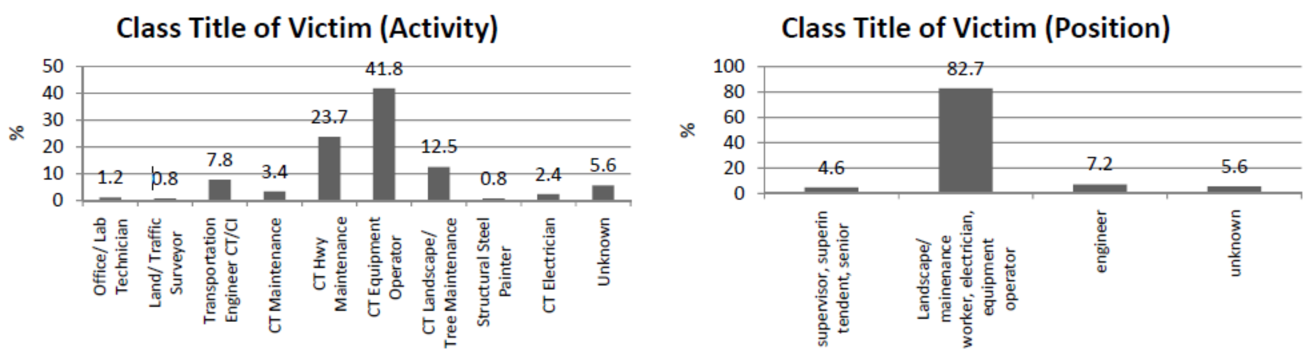


Figure 2.13: Breakdown of job title and activity of the injured worker.

2.4.1 Evaluation of Explanatory Variables

Both the CORR and REG procedures were performed using SAS, on two subsets of explanatory variables, which correspond to the two different regression analyses to be performed.

Pearson Correlation Coefficient

Prob > |r| under H0: Rho = 0

	VMT	Time Code	Weather Code	Visibility Code	Activity Type	Location	Approximate Speed Limit	Duration	PPE
VMT	1.0000	-0.0396	-0.2281	-0.1075	0.0416	-0.0912	-0.1695	0.0195	-0.0987
		0.4837	<.0001	0.0567	0.4620	0.1062	0.0025	0.7442	0.0803
Time Code	-0.0396	1.0000	0.0934	0.0104	-0.0220	-0.0573	-0.0197	0.0730	0.0159
	0.4837		0.0981	0.8541	0.6974	0.3104	0.7274	0.2212	0.7785
Weather Code	-0.2281	0.0934	1.0000	0.5293	-0.0445	0.0238	0.0820	0.0778	0.0567
	<.0001	0.0981		<.0001	0.4313	0.6735	0.1465	0.1919	0.3160
Visibility Code	-0.1075	0.0104	0.5293	1.0000	0.0082	0.0221	0.0518	-0.0034	-0.0267
	0.0567	0.8541	<.0001		0.8853	0.6958	0.3598	0.9550	0.6376
Activity Type	0.0416	-0.0220	-0.0445	0.0082	1.0000	0.0908	0.0936	-0.0353	0.0053
	0.4620	0.6974	0.4313	0.8853		0.1077	0.0972	0.5544	0.9251
Location	-0.0912	-0.0573	0.0238	0.0221	0.0908	1.0000	0.6385	0.0647	-0.0202
	0.1062	0.3104	0.6735	0.6958	0.1077		<.0001	0.2778	0.7216
Approximate Speed Limit	-0.1695	-0.0197	0.0820	0.0518	0.0936	0.6385	1.0000	0.0619	0.0106
	0.0025	0.7274	0.1465	0.3598	0.0972	<.0001		0.2997	0.8508
Duration	0.0195	0.0730	0.0778	-0.0034	-0.0353	0.0647	0.0619	1.0000	-0.0808
	0.7442	0.2212	0.1919	0.9550	0.5544	0.2778	0.2997		0.1754
PPE	-0.0987	0.0159	0.0567	-0.0267	0.0053	-0.0202	0.0106	-0.0808	1.0000
	0.0803	0.7785	0.3160	0.6376	0.9251	0.7216	0.8508	0.1754	

Figure 2.14: Summarized PROC CORR output from SAS logistic regression model.

The first variable reduction occurred with the combination of the Visibility and the Weather Code variables into a new explanatory variable named 'Conditions'. The Pearson correlation coefficient between the two separate variables was equal to 0.5293, with a corresponding *p − value* of < 0.0001. The new Conditions variable takes a value of 0, 1, or 2, corresponding to the added values of the previous two explanatory variables as shown in Table 2.12. The correlation values output for the new Conditions variable are TOL=0.8295 and VIF =1.2056, which show no correlation or co linearity with other variables.

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Tolerance	Variance Inflation
Intercept	1	-0.94377	25.84287	-0.04	0.9709	.	0
VMT	1	0.11666	0.02877	4.06	<.0001	0.86071	1.16184
Time Code	1	-0.10815	0.11399	-0.95	0.3436	0.95555	1.04652
Weather Code	1	0.24013	0.07846	3.06	0.0024	0.55165	1.81273
Visibility Code	1	0.06277	0.08668	0.72	0.4696	0.60027	1.66593
Activity Type	1	0.30306	0.06729	4.50	<.0001	0.96605	1.03515
Location	1	0.00454	0.03358	0.14	0.8926	0.93315	1.07164
Approximate Speed Limit	1	0.00825	0.39759	0.02	0.9835	0.99995	1.00005
Duration	1	-0.01779	0.03594	-0.49	0.6211	0.92542	1.08059
PPE	1	0.15099	0.06560	2.30	0.0221	0.93512	1.06938

Figure 2.15: PRC REG output for SAS logistic regression model.

Conditions	Weather/roadway conditions	Visibility	Sum (Weather + Visibility)
C_0	0 : *Clear/dry*	0 :> 1/2 mile	0
C_1 C_1	1 : *wet/snowy* or 0 : *Clear/dry*	0 :> 1/2 mile or 1 :< 1/2 mile	1 1
C_2	1 : *Wet/snowy*	1 :< 1/2 mile	2

Table 2.12: Definition of new variable Conditions.

The correlation table Figure 2.14 also showed high correlation statistics between Approximate Speed Limit and Location of Accident. This result was not unexpected as, in many cases, where the speed limit data were missing, the speed limit was selected based on the roadway type. Based on the collinearity, and the missing data, the Approximate Speed Limit variable was dropped from the analysis.

The possibility of multicollinearity existed between the VMT and Conditions variables, based on the correlation table. However, the tolerance values for both variables were large (TOL < 0.4), so both variables remained in the model.

The collinearity analysis for the second group of regression parameters contained similar results to the first. In addition, the variable Accident Type was removed based on the collinearity diagnostics (TOL=0.3959, VIF =2.8910). There was evidence of possible collinearity between other variable pairs existed(VMT–Conditions, Activity Type–Intrusion Angle, Activity Type–ISS), however the variance inflation factors for these variables were not a cause for concern, so the explanatory variables were left in the model.

2.4.2 Logistic Regression

Methods

Following the model building procedure described by Kutner, et al., [16], variable selection for the logistic procedure was performed using a stepwise selection method.

Summary of Stepwise Selection						
Step	Effect Entered	Effect Effect Removed	Number In	Score Chi-Square	Wald Chi-Square	Pr > ChiSq
1	Activity Type		1	51.4091		<.0001
2	Conditions		2	6.3799		0.0412
3	Location of Accident		3	10.6635		0.0585
4		Location of Accident	2		5.1249	0.4008

Figure 2.16: Logistic regression variable selection procedure.

The model initiated with an intercept term only, as shown in Figure 2.16. PROC LOGISTIC then selected the most significant explanatory variable, Activity Type to add to the model ($p-value < 0.0001$). Following evaluation, the Wald Chi-square met SLSTAY specifications, so the variable remained in the model. The second step of variable selection began with selecting the most significant of the remaining explanatory variables, Conditions, whose $p-value$ was equal to 0.0412. Again, the Wald Chi-square $p-value$ was within the specified range so the variable remained in the model. In the third step of variable selection, SAS chose Location as the next variable to enter the model, with a $p-value$ equal to 0.0585. However, upon evaluation, the Wald Chi-square $p-value$ for the variable in the model was greater than 0.4 ($p-value$ =0.4008). Therefore, step five involved the removal of the Location variable from the model. Because the same variable was added and removed from the model in successive steps, the selection process was terminated. The final model relates injury to a linear combination of Activity Type and Conditions.

Three additional models were created for predicting injury outcome based on common knowledge of variables understood to influence injury risk on highway work zones. Model A refers to the model created by stepwise selection, where Models B, C and D are the alternate models:

Model A:

Probability of Injury = $\alpha + \beta_1$(Activity Type)+β_2(Conditions)

Model B:

Probability of Injury = $\alpha + \beta_1$(Activity Type)+β_2(Duration)+β_3(VMT)

Model C:

Probability of Injury = $\alpha + \beta_1$(Conditions)+β_2(VMT)+β_3(Time Code)

Model D:

Probability of Injury = $\alpha + \beta_1$(Activity Type)+β_2(Duration) + β_3(Time Code)+β_4(PPE)

The explanatory variables chosen to make up Model B were selected to recreate, as closely as possible, the regression model created by Qi et al.,[19], in their study of the frequency of accidents, specifically rear end crashes, in work zones. Qi found that work zone type, traffic control devices, traffic/work zone layout, lane blockage, work zone duration, facility type, and AADT (annual average daily traffic) were associated with the frequency of rear end accidents. Therefore, the independent variables selected that most closely characterize this previous statistical model were Activity Type, Duration, Location, and VMT.

Model C was build using a subgroup of explanatory variables that represent roadway and environmental variables. The non-work zone parameters included Location, VMT, Time Code, and Conditions. Conversely, the variables selected for Model D were selected on the premise that they are variables controllable during work zone planning. Model D contained the explanatory variables representing Activity Type, Duration, Time Code, and PPE. (The variable Location was removed from

Models B and C after the first iteration as it caused the models to experience quasi-complete separation.)

By evaluating the available regression diagnostic statistics, comparisons were made between the four models and the ‘best’ model was selected. Table 2.13 shows the results of the diagnostic statistics. The deviance and Pearson’s goodness of fit statistics test the hypothesis that the model is as good as the saturated model, and that the model is appropriate. Based on these two statistics, Models A,B and D provide a better fit to the data. The Hosmer-Lemeshow statistic also tests model goodness of fit by grouping the data into sets based on the estimated probabilities. The statistics support the null hypothesis that the fitted model is adequate, with a more convincing (larger) *p − value* occurring in Model D, and similar values in all other models.

In addition, predictive power must also be evaluated to ensure that the model both fits the data and does an adequate job of predicting the injury occurrence. The statistics in Table 2.13 reflect that except for Model C, all other models rate equally in their respective predictive power.

Deviance and Pearson Goodness of Fit Statistics

	Model A	Model B	Model C	Model D
Deviance				
Value	62.8743	5.5364	16.8601	3.2852
Pr > ChiSq	1.000	0.9376	0.0510	0.9985
Pearson				
Value	141.7072	5.4623	16.2527	2.4006
Pr > ChiSq	0.2096	0.9407	0.0618	0.9997
Hosmer-Lemeshow Goodness of Fit Test				
Chi-square	0.8583	4.0106	2.3510	1.2118
Pr > ChiSq	0.6511	0.6752	0.6715	0.9763
Predictive Power				
% Concordant	78.0	84.5	48.9	83.9
% Discordant	3.4	9.6	28.9	8.3
% Tied	18.6	6.0	22.2	7.8
Pairs	7046	7046	7046	7046
Somers’ D	0.746	0.749	0.199	0.757
Gamma	0.917	0.797	0.256	0.821
Tau-a	0.120	0.120	0.032	0.121
c	0.873	0.875	0.600	0.878
Max-rescaled R-Square	0.3967	0.3833	0.0501	0.3820

Table 2.13: Logistic regression diagnostic results.

The final model evaluation involves examination of model residuals and influence points, shown in Figure 2.17. One outlying observation exists; however, all other Pearson and deviance residuals have an absolute value of approximately 2 or less. Evaluation of the DFBETAS, (Figure 2.18), shows that the most extreme values are less than 1 in Models B and D. These two diagnostics verify the assumption that the outlying case is not influential.

Overall, Models B and D are similar in goodness of fit, predictive power and treatment of residuals. Model B was chosen as the 'best' model as it agrees with previous research and the fit of the Poisson regression models following in the next section.

Results

The output of the LOGISTIC procedure is very descriptive, giving detailed model information, class level information, frequency distribution of the class variables, deviance and model fit statistics, global null hypothesis tests, Type 3 analysis results, maximum likelihood estimates, odds ratio, and predictive power measures.

Fit statistics and predictive power measures were used to determine which model was the best predictor of injury severity. Figure 2.19 shows the three sections of the SAS output important for model analysis. The first section of interest in Figure 2.19 is the 'Type 3 Analysis of Effects'. This test evaluates the main effects in the model, testing the null hypothesis that the parameter estimate is equal to zero ($H_o : \beta = 0$). These results are similar to those presented in the next output section, 'Analysis of Maximum Likelihood Estimates' in that both test the null hypothesis that $\beta = 0$. However, the maximum likelihood estimate evaluates the significance of each level of the explanatory variable. In addition to testing the significance, the maximum likelihood estimates also lists the parameter estimates and their standard error. Finally, the third section of output shown gives the 'Odds Ratio Estimates', which are derived by taking the exponential of the parameter estimate (e^{β}).

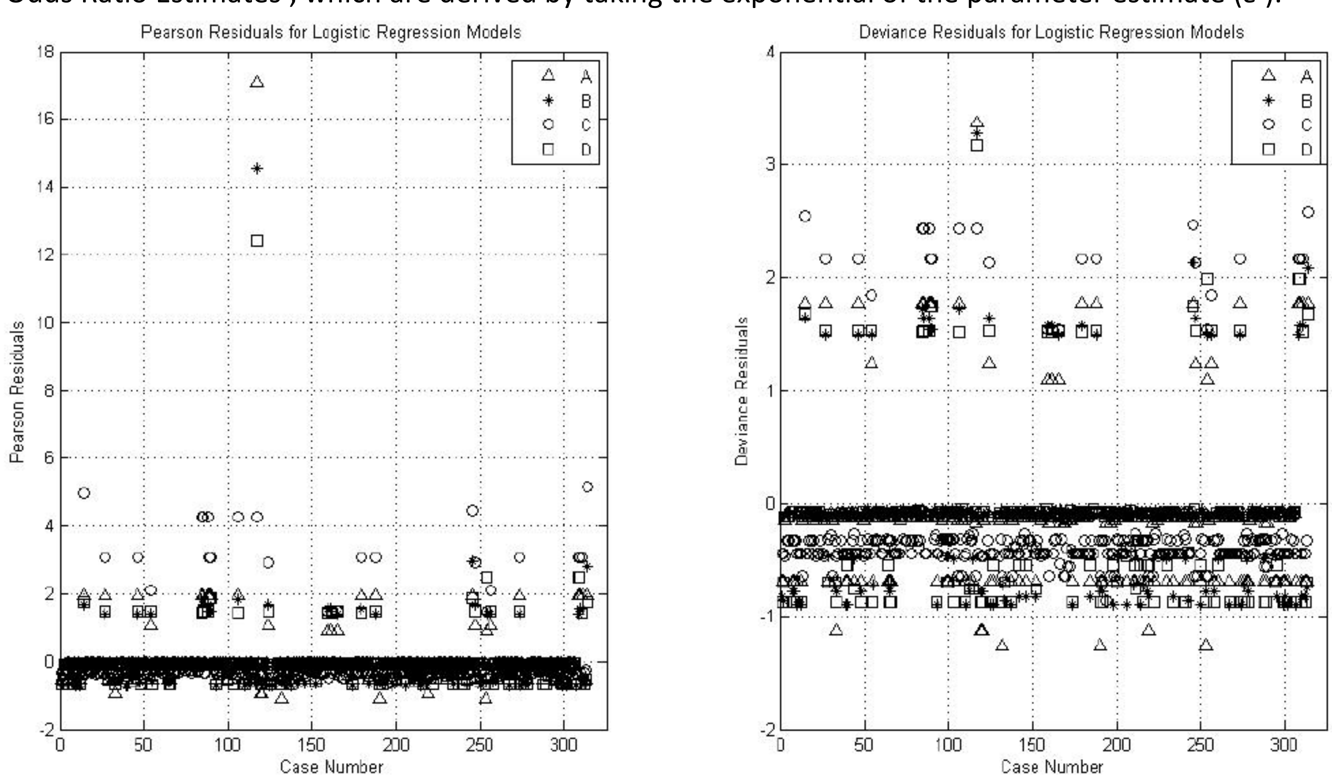


Figure 2.17: Logistic regression residual plots.

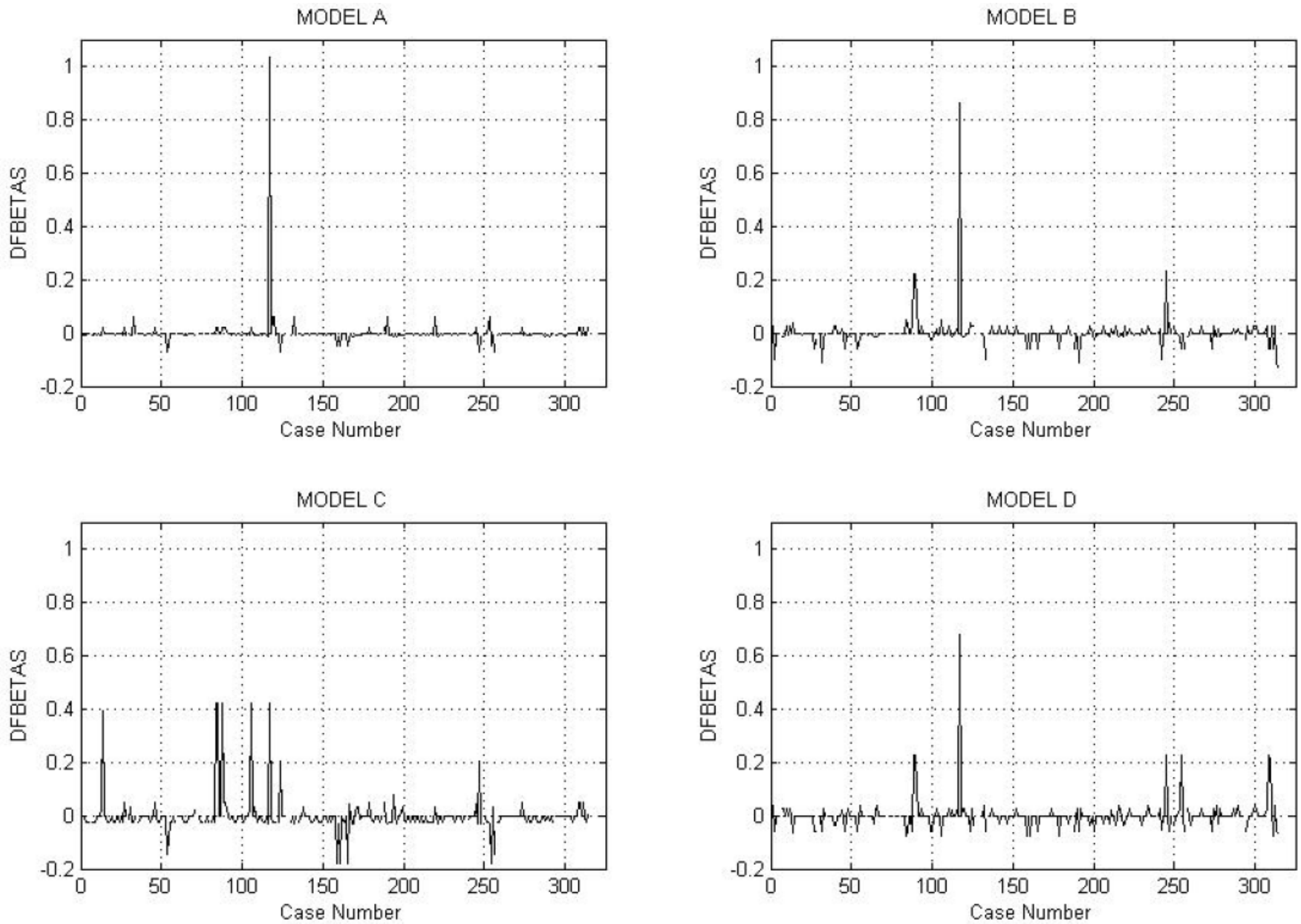


Figure 2.18: DFBETAs plot for logistic regression.

Type 3 Analysis of Effects

Effect	DF	Wald Chi-Square	Pr > ChiSq
VMT	2	2.7384	0.2543
Duration	2	0.1168	0.9433
Activity Type	1	17.3692	<.0001

Analysis of Maximum Likelihood Estimates

Parameter		DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept		1	-5.4550	1.2308	19.6439	<.0001
VMT	2	1	-1.0045	0.8700	1.3332	0.2482
VMT	3	1	0.3383	0.5040	0.4505	0.5021
Duration	mobile	1	0.1017	0.7325	0.0193	0.8895
Duration	short duration	1	-0.0763	0.8140	0.0088	0.9253
Activity Type	On Foot	1	4.2996	1.0317	17.3692	<.0001

Odds Ratio Estimates

Effect			Point Estimate	95% Wald Confidence Limits	
VMT	2 vs 1		0.366	0.067	2.015
VMT	3 vs 1		1.403	0.522	3.767
Duration	mobile	vs short-term stationary	1.107	0.263	4.652
Duration	short duration	vs short-term stationary	0.927	0.188	4.568
Activity Type	On Foot vs Driving		73.673	9.753	556.511

Figure 2.19: Condensed output from the SAS LOGISTIC procedure for the model predicting the probability of a worker obtaining a non-minor injury.

The best way to interpret the parameter estimates produced by the logistic regression is to use the odds ratio. Referring to Figure 2.19, point estimates are available for each level of the three explanatory variables in the regression model. The odds of a worker receiving a non-minor injury are approximately 74 times greater for a worker on foot compared to workers working from a vehicle, conditional on all other variables. The Activity Type is the most significant variable with a Type 3 Analysis $p - value$ of < 0.0001. The second most significant main effect is the VMT variable, ($p - value$ =0.2543), which is not statistically significant. The odds of receiving a non-minor injury are about 1.5 times greater for work taking place in regions declared as high VMT areas compared to low VMT areas. However, the odds of being seriously injured decrease in areas of medium level VMT, compared to areas of low VMT. The odds ratio for a given level is only valid if all other explanatory variables remain constant. The third variable in the model, Duration also does not have a significant effect on the model. However, its inclusion in the model produced better fit statistics and predictability. According to the logistic regression model, workers in mobile work zones are 1.1 times more likely to be severely injured compared to workers in short-term stationary work zones. The likelihood of being severely injured decreases for workers in short duration work zones.

While evaluation of the odds ratio is the preferred way of logistic regression model analysis, the predicted probability can also be determined. The predicted probability of obtaining a non-minor injury based on activity type, and work zone duration, and for three different VMT regions was calculated, and is shown in Figure 2.20.

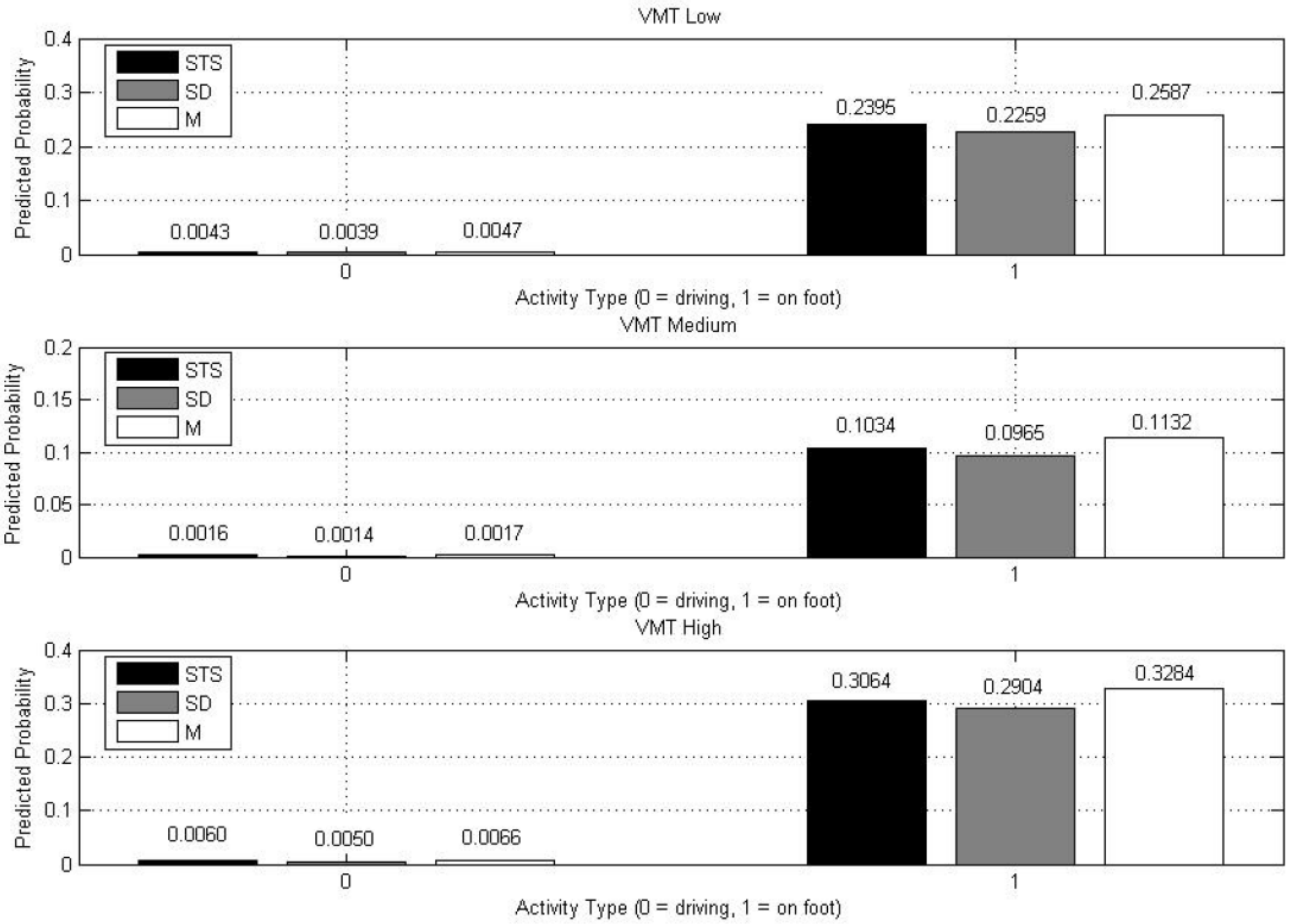


Figure 2.20: Predicted probability of obtaining a serious injury based on Activity Type, work zone Duration and VMT. (STS: Short-term Stationary, SD: Short Duration, M: Mobile)

Interpretation of the first figure, for VMT = 1, or areas of low Vehicle Miles Traveled, is as follows: For short-term stationary work zones, the probability of obtaining a non-minor injury increases from 0.46% to 23.95% when the worker moved from performing work in a vehicle to work on foot. In short duration work zones, the probability of severe injuries increases in the same manner as short-term stationary work zones; however, it does not change as much (0.39% to 22.59%). The final analysis for areas of low VMT shows that in mobile work zones, the probability of severe injury increases from 0.47% for workers in vehicles to 25.87% for workers on foot. In the two graphs following, for medium and high levels of VMT, the probability of obtaining a non-minor injury increased for all durations when comparing the predicted probability of serious injury for workers working from vehicle to workers performing duties on foot. In all three VMT regions, the largest increase is observed in mobile work zones, followed by short-term stationary work zones, and finally short duration work zones. While there are differences in the predicted probability, the differences between the three work zone durations levels for workers on foot is not significant, as the corresponding $p-value$s for duration are 0.9253 (short duration) and 0.8895 (mobile). Additionally, the predicted probability plots show the change in probability over the three specified levels of VMT. For all categories, the probability of injury is highest in areas of high VMT, or areas of high traffic volume. Conversely, the lowest probability of non-minor injury occurred, for all variables combinations, in areas rated as medium VMT.

2.4.3 Poisson Regression

Methods

Backward selection was used to select variables for the Poisson regression models. The selection process for both the Modified and Lost Time models is shown in Table 2.14 and Table 2.15.

Modified Time Model

Step	Effect in Model	Effect Removed	$p-value$
1	Location, AIS Body Region, VMT, Time Code, ISS, Conditions, Intrusion Angle, Activity Type, Duration, PPE	None	-
2	Location, AIS Body Region, VMT Time Code, ISS, Conditions, Activity Type, Duration, PPE	Intrusion Angle	Type 1 = 0.8608 Type 3 = 0.8698
3	Location, AIS Body Region, VMT Time Code, ISS, Conditions, Activity Type, PPE	Duration	Type 1 = 0.8100 Type 3 = 0.8100
4	Location, AIS Body Region, VMT Time Code, ISS, Conditions, Activity Type	PPE	Type 1 = 0.6158 Type 3 = 0.6158
5	Location, AIS Body Region, VMT Time Code, ISS, Conditions,	Activity Type	Type 1 = 0.3983 Type 1 = 0.5626

Table 2.14: Steps of backward variable selection for the Modified Time Model.

Three additional models were created for each dependent variable. Construction of the three alternate models occurred in two steps. The first step followed the same procedures used to create alternate models B, C, and D in the logistic regression analysis of the same data set. To reiterate, the three models were created to group together independent variables known to have an effect on work zone safety. Model B (for both Modified and Lost Time models) recreated, using the available variables, the regression model found to influence work zone accident frequency by Qi, et al., [19].

Lost Time Model

Step	Effect in Model	Effect Removed	$p - value$
1	Location, AIS Body Region, VMT, Time Code, ISS, Conditions, Intrusion Angle, Activity Type, Duration, PPE	None	-
2	Location, AIS Body Region, VMT Time Code, ISS, Conditions, Intrusion Angle, Activity Type, Duration	PPE	Type 1 = 0.7567 Type 3 = 0.7567
3	Location, AIS Body Region, Time Code, ISS, Conditions, Intrusion Angle, Activity Type, Duration	VMT	Type 1 = 0.4263 Type 3 = 0.5175

Table 2.15: Steps of backward variable selection for the Modified Time Model.

Model C included predictor variables relating roadway and environmental factors, where Model D evaluated the relationship between the dependent variable and explanatory variables describing parameters that can be controlled by work zone planning. The variables used to make up alternate models B, C and D are shown below. (Separate models were created for each dependent variable, although they are shown together here.)

Model B:

Estimated Modified or Lost Time = $\alpha + \beta_1$(Activity Type)+β_2(Duration)+β_3(VMT)+β_4(Location)

Model C:

Estimated Modified or Lost Time = $\alpha + \beta_1$(Conditions)+β_2(VMT)+β_3(Time Code)+β_4(Location)

Model D:

Estimated Modified or Lost Time = $\alpha + \beta_1$(Activity Type)+β_2(Duration)+β_3(Time Code)+β_4(PPE)

A second step was necessary to add injury and accident parameters into the regression model. However, before more variables were added, Models B, C and D were compared to identify the Poisson regression model with the best fit and residual plots. The diagnostics are shown in Table 2.16.

For both Modified and Lost Time regression models, Model B had the best fit. After selecting the best alternate model, three subgroups of injury and/or accident parameters we added to the model. The four resulting models, in addition to Model A, are shown below:

Modified Time Model Diagnostics

Criteria for Assessing Goodness of Fit

	Model B	Model C	Model D
Deviance	42.9221	42.7756	48.4693
Scaled Deviance	1.0000	1.0000	1.0000
Pearson Chi-Square	103.2321	97.7065	171.0363
Scaled Pearson	2.4051	2.2842	3.5288
Overdispersion Parameter			
Scale	6.5515	6.5403	6.9620

Lost Time Model Diagnostics

Criteria for Assessing Goodness of Fit

	Model B	Model C	Model D
Deviance	52.8147	60.3475	57.7988
Scaled Deviance	1.0000	1.0000	1.0000
Pearson Chi-Square	108.6865	124.6542	126.9927
Scaled Pearson	2.0579	2.0656	2.1972
Overdispersion Parameter			
Scale	7.2674	7.7684	7.6026

Table 2.16: Deviance and Pearson's Chi-square goodness of fit statistics for the Modified and Lost time regression models.

Modified Time Model A

Estimated Modified Time = $\alpha + \beta_1$(Location)+β_2(VMT)+β_3(Time Code)+
β_4(AIS Body Region)+β_5(ISS)+
β_6(Activity Type)

Lost Time Model A

Estimated Lost Time = $\alpha + \beta_1$(Activity Type)+β_2(VMT)+
β_3(Duration)+β_4(Time Code)+β_5(Location)+
β_6(ISS)+β_7(Conditions)+β_8(Intrusion Angle)+
β_9(AIS Body Region)+β_{10}(PPE)

Alternate Model B1

Estimated Modified or Lost Time = $\alpha + \beta_1$(VMT)+β_2(Duration)+
β_3(Location)+β_4(Activity Type)

Alternate Model B2

Estimated Modified or Lost Time = $\alpha + \beta_1$(VMT)+β_2(Duration)+β_3 (Location)+
β_4(Activity Type)+β_5(AIS Body Region)+
β_6(ISS)

Alternate Model B3

Estimated Modified or Lost Time = $\alpha + \beta_1$(VMT)+β_2(Duration)+β_3(Location)+

β_4(Activity Type)+β_5(Intrusion Angle)

Alternate Model B4

Estimated Lost or Modified Time = α + β_1(VMT)+β_2(Duration)+β_3(Location)+

β_4(Activity Type)+β_5(AIS Body Region)+

β_6(ISS)+β_7(Intrusion Angle)

Recall that Model A was created by backward selection, starting with all explanatory variables, and models B1 through B4 (identical for Modified and Lost Time dependent variables) were created using groups of parameters known to affect work zone safety.

Examination of the Modified Time model, Table 2.17 shows the values of the goodness of fit statistics for each of the five models. Two goodness of fit statistics are available from the GENMOD procedure. These statistics do not provide the same information as logistic regression diagnostics, rather, they are used to determine the adequacy of a model in comparison with another model under consideration. If the model fits the data well, the ratio of the deviance (or Pearson Chi-square) value to the degrees of freedom (Value/DF) should be close to 1, values greater than 1 indicate over-dispersion. When this occurs, as it did in the California injury data, an over-dispersion parameter, or a free scale parameter, is defined. The scaled deviance is force to equal one by specifying the over-dispersion criteria as SCALE = DEVIANCE in the model statement. Allowing for over-dispersion has no effect on the regression Coefficients, however, it effects the associated $p - value$s and confidence intervals.

Of the five models for Modified Time, Models A, B2 and B4 have similar goodness of fit statistics, and lower dispersion parameters. Evaluation of the influence plots, shown in Figure 2.21, shows the presence of a possible outlier. Upon examination of the data point, certain data fields in case number 203 may have been entered in error, thus, this outlying observation was removed. The model diagnostics for Models A, B2 through B4, with outlying case 203 removed are shown in Table 2.17. The model fit improved with the removal of the observation; however, in general, the fit of the models, relative to one another did not change. Overall, the influence plots show that the residuals are treated well in each model (Figure 2.22). Based on the goodness of fit statistics, and the influence plots, Model B4 was selected to be the best regression model relating Modified Time to selected work zone accident parameters. Model B4 will be a better predictive model, as it considers the effect of more independent variables.

Criteria for Assessing Goodness of Fit

	Model A	Model B1	Model B2	Model B3	Model B4
Deviance	41.4524	42.9221	42.0767	43.1835	42.4715
Scaled Deviance	1.0000	1.0000	1.0000	1.0000	1.0000
Pearson Chi-Square	84.6804	103.2321	81.7773	99.4189	81.2838
Scaled Pearson	2.0428	2.4051	1.9435	2.3022	1.9138

Over dispersion Parameter

Scale	6.4384	6.5515	6.4867	6.5714	6.5170

Criteria for Assessing Goodness of Fit -Outlier Removed

	Model A	Model B1	Model B2	Model B3	Model B4
Deviance	28.1456	30.6654	29.3697	30.9668	29.6721
Scaled Deviance	1.0000	1.0000	1.0000	1.0000	1.0000
Pearson Chi-Square	42.1835	46.4138	43.1022	46.9819	43.4872
Scaled Pearson	1.4988	1.5136	1.4676	1.5172	.4656

Over dispersion Parameter -Outlier Removed

Scale	5.3052	5.5376	5.4194	5.5648	5.4472

Table 2.17: Poisson regression diagnostics for Modified Time models.

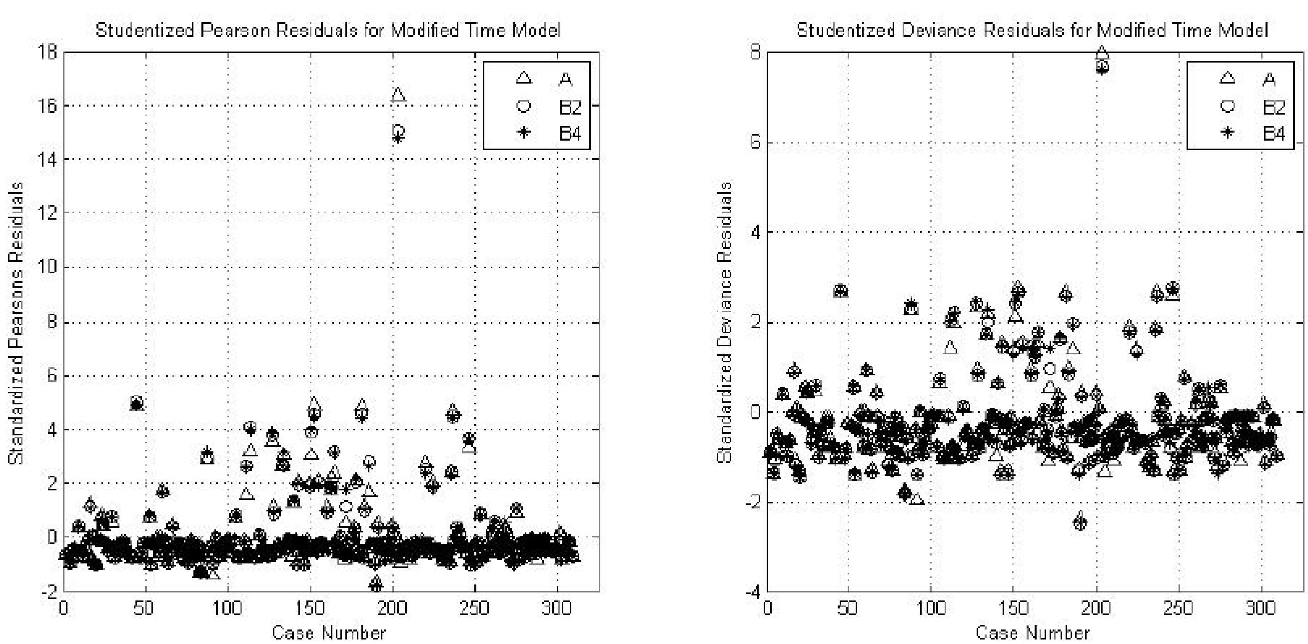


Figure 2.21: Poisson regression studentized residual plots for Modified Time Models A, B2 and B4.

Model selection for the Lost Time regression model was approached in a similar manner. Of the five ‘good’ models, Model A had the most agreeable goodness of fit statistics, and a slightly smaller dispersion parameter (Table 2.18). The influence plots show that the treatment of the studentized residuals does not differ greatly between the models (Figure 2.23). The outlying observation in the Lost Time data does not appear to be an error in data entry, thus it remains in the model. Since the purpose of this model, similar to those before it, is to predict injury severity (via lost time) based on a number of work zone parameters, Model A was selected, as it was the model including the largest number of explanatory variables, and has good fit and treats the residuals well.

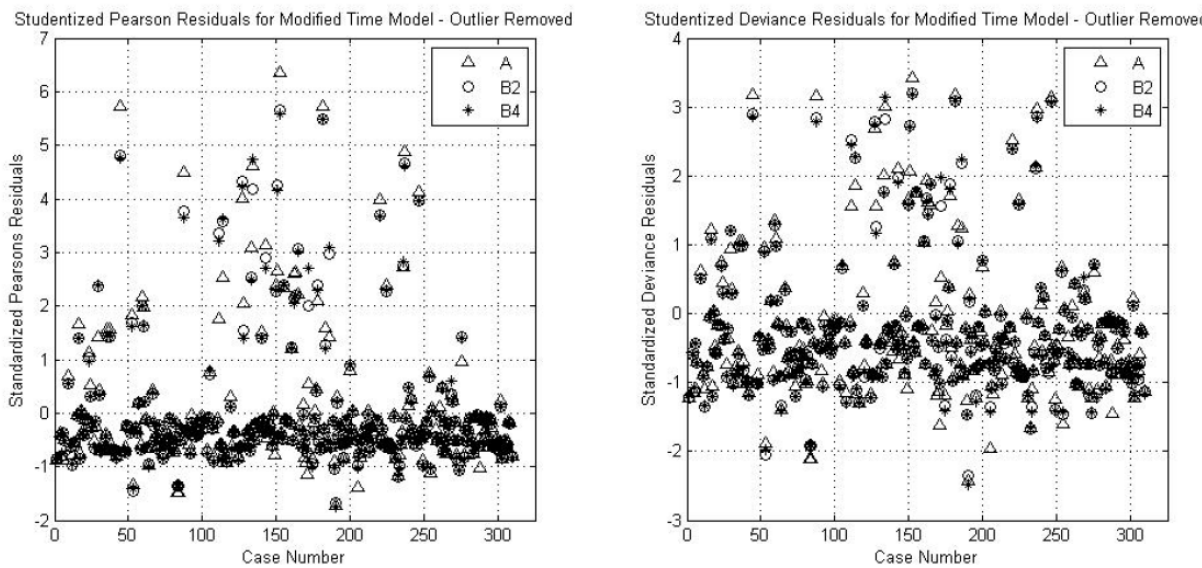


Figure 2.22: Poisson regression studentized residual plots for Modified Time Models A, B2 and B4, with outlying observation removed.

Criteria for Assessing Goodness of Fit

	Model A	Model B1	Model B2	Model B3	Model B4
Deviance	49.5474	52.8147	52.1250	51.9286	51.1817
Scaled Deviance	1.0000	1.0000	1.0000	1.0000	1.0000
Pearson Chi-Square	133.0626	108.6865	109.3724	111.9425	111.2244
Scaled Pearson	2.6856	2.0579	2.0983	2.1557	2.1731

Over-dispersion Parameter

Scale	7.0390	7.2674	7.2198	7.2062	7.1541

Table 2.18: Poisson regression diagnostics for Lost Time models.

Results

Abridged Poisson regression outputs produced by the GENMOD procedure for the two regression models (Modified Time, Lost Time) are shown in Figure 2.24, through Figure 2.27. The four important groups of statistical output are listed under the 'Criteria for Assessing Goodness of Fit', 'Analysis of Parameter Estimate', 'LR Statistics for Type 1 Analysis' and 'LR Statistics for Type 3 Analysis' headings. The goodness of fit statistics, described previously, were used in model selection.

The second section of output gives the estimated Poisson regression Coefficients for the model, the Wald 95% confidence intervals for each individual regression Coefficient, and the chi-square statistic and associated $p - value$. The chi-square statistic tests the null hypothesis that an individual predictors regression Coefficient is zero ($H_o : \beta = 0$), given that the rest of the predictors are in the model. The probability that any particular chi-square test statistic is as extreme as, or more so, than what was observed under H_o is defined by Pr > ChiSq.

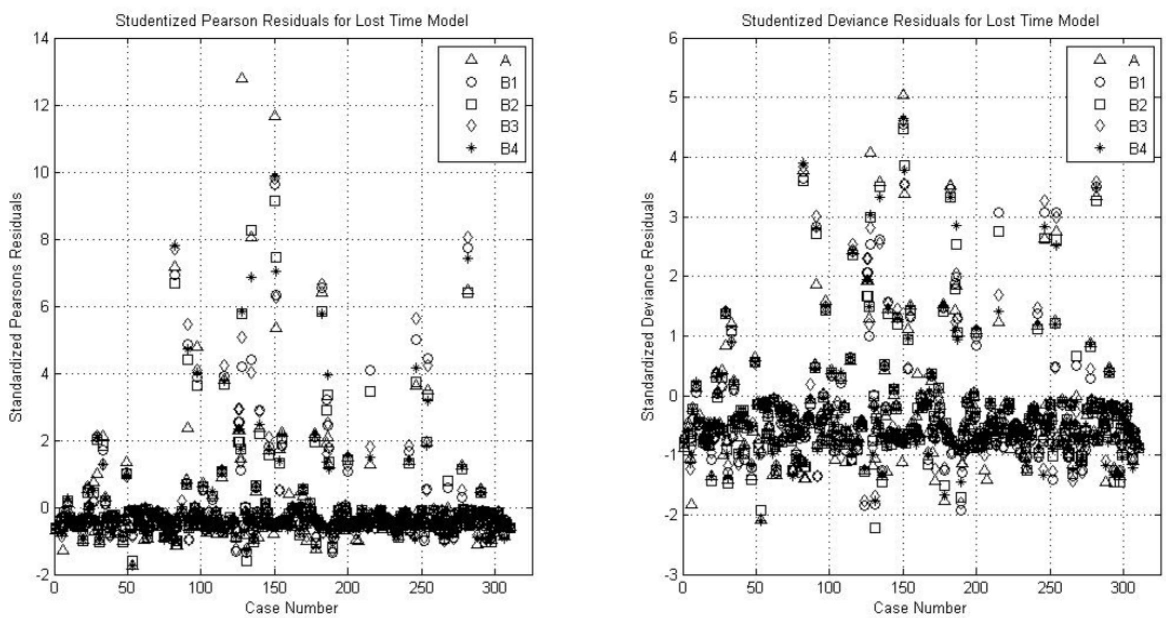


Figure 2.23: Poisson regression studentized residual plots for Lost Time.

Parameter		Estimate	Wald 95% Confidence Limits		Chi-Square	Pr>ChiSq	Odds Ratio
Intercept		1.4499	-1.2053	4.1051	1.15	0.2845	
VMT	(3)	-0.3167	-0.7533	0.1198	2.02	0.1550	0.7285
VMT	(2)	-1.0398	-2.0029	-0.0766	4.48	0.0344	0.3535
VMT	(1)	0.0000	0.0000	0.0000	.	.	1.0000
Duration	(STS)	0.0523	-0.5532	0.6579	0.03	0.8655	1.0537
Duration	(SD)	0.2457	-0.2562	0.7475	0.92	0.3373	0.2785
Duration	(M)	0.0000	0.0000	0.0000	.	.	1.0000
Location	(Shoulder Closure)	1.2188	-1.0662	3.5038	1.09	0.2958	3.3831
Location	(Moving Lane Cl)	1.4759	-0.7868	3.7386	1.63	0.2011	4.3750
Location	(Freeway/Highway)	1.6967	-0.4686	3.8620	2.36	0.1246	5.4559
Location	(Freeway Ramp)	-1.9792	-6.3327	2.3743	0.79	0.3729	0.1382
Location	(Freeway Lane Cl)	-0.5363	-3.7285	2.6559	0.11	0.7419	0.5849
Location	(City Street)	0.0000	0.0000	0.0000	.	.	1.0000
Activity Type	(On Foot)	0.2598	-0.2665	0.7861	0.94	0.3333	1.2967
Activity Type	(Driving)	0.0000	0.0000	0.0000	.	.	1.0000
Body Region	(Whole Body)	-0.7003	-1.8286	0.4279	1.48	0.2238	0.4964
Body Region	(Upper Extremity)	-0.6134	-1.7626	0.5358	1.09	0.2955	0.5415
Body Region	(Spine)	-1.1362	-2.1903	-0.0820	4.46	0.0347	0.3210
Body Region	(Neck)	-2.2344	-3.7758	-0.6930	8.07	0.0045	0.1071
Body Region	(Lower Extremity)	-0.5170	-1.6208	0.5868	0.84	0.3586	0.5963
Body Region	(Head/Face)	-1.0323	-2.3476	0.2830	2.37	0.1240	0.3562
Body Region	(Abdomen/Thorax)	0.0000	0.0000	0.0000	.	.	1.0000
ISS		0.1001	-0.0351	0.2353	2.11	0.1467	1.1053
Intrusion Angle	(Sideswipe)	0.3527	-0.8708	1.5763	0.32	0.5721	1.4229
Intrusion Angle	(Rear end)	0.2483	-0.9181	1.4147	0.17	0.6765	1.2818
Intrusion Angle	(Head on)	0.2108	-1.2829	1.7045	0.08	0.7821	1.2347
Intrusion Angle	(Broadside)	0.0000	0.0000	0.0000	.	.	1.0000
Scale		5.4472	5.4472	5.4472			

Analysis Of Parameter Estimates

NOTE: The scale parameter was estimated by the square root of DEVIANCE/DOF.

Figure 2.24: Partial Poisson regression output for the Modified Time model.

Analysis Of Parameter Estimates

Parameter		Estimate	Wald 95% Confidence Limits		Chi-Square	Pr>ChiSq	Odds Ratio
Intercept		1.2473	-1.8437	4.3382	0.63	0.4260	
Activity Type	(On Foot)	1.1736	0.5956	1.7516	15.84	<.0001	3.2336
Activity Type	(Driving)	0.0000	0.0000	0.0000	.	.	1.000
VMT	(3)	-0.0773	-0.5756	0.4210	0.09	0.7610	0.9256
VMT	(2)	-2.9962	-5.0986	-0.8939	7.80	0.0052	0.0500
VMT	(1)	0.0000	0.0000	0.0000	.	.	1.0000
Duration	(STS)	0.6993	0.1546	1.2440	6.33	0.0119	2.0123
Duration	(SD)	-0.7008	-1.4239	0.0223	3.61	0.0575	0.4962
Duration	(M)	0.0000	0.0000	0.0000	.	.	1.0000
Time_Code	(1)	1.0590	0.3578	1.7602	8.76	0.0031	2.8835
Time_Code	(0)	0.0000	0.0000	0.0000	.	.	1.0000
Location	(Shoulder Cl)	-0.1940	-1.7773	1.3893	0.06	0.8102	0.8237
Location	(Moving Lane Cl)	0.7651	-0.7605	2.2906	0.97	0.3257	2.1492
Location	(Freeway/Highway)	0.8162	-0.5404	2.1728	1.39	0.2383	2.2619
Location	(Freeway Ramp)	0.4101	-1.3147	2.1349	0.22	0.6412	1.5070
Location	(Freeway Lane Cl)	-2.7248	-7.8097	2.3601	1.10	0.2936	0.0656
Location	(City Street)	0.0000	0.0000	0.0000	.	.	1.0000
ISS		0.1409	-0.0096	0.2915	3.37	0.0666	1.1513
Conditions	(2)	-1.1508	-2.3208	0.0192	3.72	0.0539	0.3164
Conditions	(1)	0.0975	-0.6297	0.8246	0.07	0.7928	1.1024
Conditions	(0)	0.0000	0.0000	0.0000	.	.	1.0000
Intrusion Angle	(Sideswipe)	-0.9685	-1.8577	-0.0793	4.56	0.0328	0.3797
Intrusion Angle	(Rear end)	-1.1482	-2.0019	-0.2944	6.95	0.0084	0.3172
Intrusion Angle	(Head on)	-0.6564	-2.0443	0.7315	0.86	0.3539	0.5187
Intrusion Angle	(Broadside)	0.0000	0.0000	0.0000	.	.	1.0000
Body Region	(Whole Body)	0.8077	-1.9027	3.5181	0.34	0.5592	2.2427
Body Region	(Upper Extremity)	0.1263	-2.6848	2.9374	0.01	0.9298	1.1346
Body Region	(Spine)	1.2927	-1.3546	3.9400	0.92	0.3385	3.6426
Body Region	(Neck)	1.4238	-1.3033	4.1509	1.05	0.3062	4.1529
Body Region	(Lower Extremity)	0.5812	-2.1279	3.2902	0.18	0.6741	1.7882
Body Region	(Head/Face)	1.1176	-1.6755	3.9108	0.62	0.4329	3.0575
Body Region	(Abdomen/Thorax)	0.0000	0.0000	0.0000	.	.	1.0000
PPE	(1)	0.2749	-0.3628	0.9126	0.71	0.3982	1.3164
PPE	(0)	0.0000	0.0000	0.0000	.	.	1.0000
Scale		7.0390	7.0390	7.0390			

NOTE: The scale parameter was estimated by the square root of DEVIANCE/DOF.

Figure 2.25: Partial SAS output for the Lost Time Poisson regression model.

The section entitled ‘LR Statistics for Type 1 Analysis’ fits a sequence of models, beginning with an intercept only model, and computes likelihood ratio statistics for each iteration. One specified explanatory variable is added at each step. Each entry of the output table gives the deviance and chi-square statistic for the model containing the effect for that row and all the proceeding effects. The statistics evaluate the model under the null hypothesis that the variable is not significant ($H_o : \beta = 0$). Thus, a low *p − value* supports the alternate hypothesis and denotes a significant variable.

The Type 3 Analysis produces similar results to Type 1 Analysis, however the procedure is slightly different. The analysis produces likelihood ratio statistics, degrees of freedom and chi-square statistics with the corresponding p−value testing the significance of the variable, $H_o : \beta = 0$. However, Type 3 Analysis tests the additional contribution of the variable in the model, given that all other variables remain in the model. Unlike Type 1 Analysis, the resulting statistics do not depend on the order of the variables.

Inferences for Poisson regression were developed in a manner similar to the method used for logistic regression interpretation, using the odds ratio. When evaluating class variables, the variable with an estimate equal to zero represents the reference value for that explanatory variable. The reference variable was chosen by SAS as the level of the classification variable with the lowest (or first, alphabetically) by specifying ORDER = DESCENDING in the CLASS statement.

Evaluation of Figure 2.24 and Figure 2.25 show that many explanatory variables, and their corresponding parameter estimates are statistically significant in the Lost Time model, while few are significant in the Modified Time Model.

The predicted parameter estimates for Activity Type have a significant effect on the mean estimated Lost Time, but not on the mean estimated Modified Time ($p - value < 0.0001$ for Lost Time, 0.3333 for Modified Time). The Lost Time parameter estimate was calculated to be 1.1736 for the 'on foot' Activity Type, and the Modified Time parameter was estimated at 0.2598. One way to interpret the estimate is to follow the log transformation to calculate the odds ratio. After adjusting for all other variables, workers on foot are predicted to experience 3.2 times as many lost work days, or 1.3 as many modified work days due to roadway work zone intrusions, compared to workers working from vehicles.

Each estimate represents the log increase or decrease the variable will have on the estimated mean number modified or lost days. The Activity Type variable is simple to analyze, as it only has two levels. However, class variables with multiple levels are more complex. For example, looking at the Location of Accident variable, we see that the reference level is City Street. Therefore, all levels of analysis will be compared to accidents which occur on city streets. Examining Figure 2.24, it is noticed that the estimated mean number of modified days for injury occurring in a Moving Lane Closure is 4.3750 times the estimated number compared to the reference location, ($p - value$ =0.2011). According to the California data, the most frequently reported location was Freeway/Highway. The Poisson regression model estimates that workers working in work zones located on a highway or freeway are expected to require 5.4559 times more modified work days that a worker involved in an accident in a city street work zone ($p - value$ =0.1246).

Looking at lost time, (Figure 2.25), the same comparisons of Moving Lane Closure and Freeway/Highway accident locations show an increase in lost days as 2.1492 and 2.2619 times the number of lost days, respectively, for the same accident on a city street(Moving Lane Closure $p - value$ =0.3257,Freeway/Highway $p - value$ =0.2383). The significance of the levels of each location are not statistically significant, but the variable is, overall, significant in the model, as will be discussed shortly.

Another type of explanatory variable used in the model was the continuous variable ISS. Figure 2.24 and Figure 2.25 show the parameter estimates and $p - value$s for ISS. The analysis results show that for every 1-unit increase in injury severity (ISS), the estimated modified time will increase by approximately 11% ($p - value$ =0.1467). Keeping with the previous interpretation, this result can be read as the estimated modified days will be 1.1053 times higher for every 1-unit increase in injury level, conditional on all other variables. Evaluating the mean estimated lost time, for every 1-unit increase in ISS, assuming all other variables remain constant, the estimated number of lost days will increase by about 15% (odds ratio = 1.1513, $p - value$ =0.0666).

Evaluation of the Type 1 and Type 3 likelihood ratio statistics provided in the output for the modified and lost time regression models, (Figure 2.26 and Figure 2.27), show that the effect of some of the variables are not significant at the α =0.05 level. However, comparison of the parameter level effect, some variables are significant overall only (Type 1 and Type 3), and some are significant only at specific levels.

For example, in both the Modified and Lost Time models, VMT, Location, and Activity Type are significant overall, but are not statistically significant in every individual level. Conversely, there are predictors that are significant at a specific level, such as the spine and neck body regions in the Modified Time model, or the sideswipe and rear end intrusion angles in the Lost Time model, which do not have statistically significant effects overall.

2.5 Discussion of Work Zone Injury Analysis

A number of conclusions can be drawn from evaluation of the injury analysis. These conclusions will increase the understanding of work zone injuries, and the parameters that may increase or decrease the risk of severe injury. In this section, the effect of each explanatory variable on the predicted probability of injury, or estimated number of modified and lost days will be discussed.

LR Statistics For Type 1 Analysis

Source	Deviance	Num DF	Den DF	F Value	Pr > F	Chi-Square	Pr > ChiSq
Intercept	9433.8007						
VMT	9149.5444	2	253	4.79	0.0091	9.58	0.0083
Duration	9120.3449	2	253	0.49	0.6120	0.98	0.6114
Location	8391.3556	5	253	4.91	0.0003	24.57	0.0002
Activity Type	8064.9909	1	253	11.00	0.0010	11.00	0.0009
AIS Body Region	7582.5023	6	253	2.71	0.0144	16.26	0.0124
ISS	7518.6551	1	253	2.15	0.1436	2.15	0.1424
Intrusion Angle	7507.0470	3	253	0.13	0.9420	0.39	0.9421

LR Statistics For Type 3 Analysis

Source	Num DF	Den DF	F Value	Pr > F	Chi-Square	Pr > ChiSq
VMT	2	253	3.02	0.0503	6.05	0.0486
Duration	2	253	0.45	0.6355	0.91	0.6350
Location of Accident	5	253	5.28	0.0001	26.38	<.0001
Activity Type	1	253	0.92	0.3377	0.92	0.3368
AIS Body Region	6	253	2.26	0.0385	13.55	0.0351
ISS	1	253	2.01	0.1572	2.01	0.1560
Intrusion Angle	3	253	0.13	0.9420	0.39	0.9421

Figure 2.26: Partial Poisson regression output for the Modified Time model.

LR Statistics For Type 1 Analysis

Source	Deviance	Num DF	Den DF	F Value	Pr > F	Chi-Square	Pr > ChiSq
Intercept	17743.4707						
Activity Type	16573.3691	1	250	23.62	<.0001	23.62	<.0001
VMT	15497.4272	2	250	10.86	<.0001	21.72	<.0001
Duration	14678.3187	2	250	8.27	0.0003	16.53	0.0003
Time Code	14476.2688	1	250	4.08	0.0445	4.08	0.0434
Location	13657.2144	5	250	3.31	0.0066	16.53	0.0055
ISS	13518.3001	1	250	2.80	0.0953	2.80	0.0940
Conditions	13261.8755	2	250	2.59	0.0772	5.18	0.0752
Intrusion Angle	12913.4898	3	250	2.34	0.0736	7.03	0.0709
AIS Body Region	12423.5107	6	250	1.65	0.1344	9.89	0.1294
PPE	12386.8463	1	250	0.74	0.3905	0.74	0.3897

LR Statistics For Type 3 Analysis

Source	Num DF	Den DF	F Value	Pr > F	Chi-Square	Pr > ChiSq
Activity Type	1	250	15.32	0.0001	15.32	<.0001
VMT	2	250	10.57	<.0001	21.14	<.0001
Duration	2	250	6.76	0.0014	13.52	0.0012
Time Code	1	250	7.76	0.0058	7.76	0.0053
Location of Accident	5	250	2.66	0.0232	13.28	0.0209
ISS	1	250	3.30	0.0707	3.30	0.0695
Conditions	2	250	2.58	0.0781	5.15	0.0761
Intrusion Angle	3	250	2.08	0.1036	6.23	0.1007
AIS Body Region	6	250	1.57	0.1571	9.40	0.1521
PPE	1	250	0.74	0.3905	0.74	0.3897

Figure 2.27: Partial SAS output for the Lost Time Poisson regression model.

The variables found to have a statistical effect on the responses were Activity Type, Duration, Location of Accident, Body Region, ISS, VMT, Time Code, Conditions, and Intrusion Angle.

Primary epidemiological evaluation of the overall California injury data set (Table 2.5, Table 2.6) showed that the majority of work zone injuries were caused by a vehicle, in either a motor vehicle collision, or a struck by motor vehicle accident. Most of the struck by object injuries occurred at non-roadway locations, or during activities not usually occurring in the work zone. Therefore, the most effective way to reduce injuries obtained in the work zone is to focus efforts on protecting workers from traveling and possibly intruding vehicles.

In all three regression models, workers performing duties on foot were predicted to experience a higher rate of serious injury, either by predicting the probability of obtaining a non-minor injury, or by estimating the mean number of modified and lost days. The logistic analysis (Figure 2.20) concluded that there was a statistically significant difference between the predicted probability of injury for workers working on the ground, compared to work activities that are carried out from inside a vehicle. Overall, based on all regression models, when all other variables are held constant, workers on foot experience a higher risk of injury.

The Duration variable was found to have an effect in both regression models. The $p-values$ associated with the Wald chi-square statistic, while not statistically significant in the logistic regression, the difference between a short-term stationary work zone and a mobile work zone is more extreme than the difference between short-term stationary and short duration work zones.

This difference is reflected in Figure 2.20, and the Poisson regression models (Figure 2.24 through Figure 2.27).

The most common location of an injury accident was reported as either a freeway or highway. In the Poisson regression models, all other locations predicted a mean estimate of fewer modified or lost days for injury accidents.

Back, or spinal, injuries were the most frequent injuries received by workers injured in California work zones. In the Poisson regression model, compared to most other body regions, spinal injuries required the highest estimated number of lost and modified work days. Only injuries to the neck and abdomen/thorax regions required more lost or modified time. The injury severity score (ISS) caused a statistically significant increase on the mean estimated days of lost time.

Based on Figure 2.5, there was a statistical trend in the time of day in which a work zone accident occurred. However, while this figure shows the trend of past injury accidents, the results of the regression models help to show the predictive effect of the time of day on the mean estimated number of lost days. According to the Poisson regression models, the estimated lost time due to an injury significantly increased based on the time of day in which the work was being performed. During peak, or rush hours, more traffic is on the roadway, increasing the exposure and risk of the worker. It is not a surprising conclusion that more serious injuries will occur during time periods of heightened exposure.

While roadway conditions cannot be controlled, they do have an effect on injury severity, and thus should be considered when designing the safety plan for a work zone, whenever possible. Overall, based on Type 1 and Type 3 analysis, the Conditions variable was not significant at the $\alpha = 0.05$ level, although at individual levels it did have a significant effect on the lost time estimate.

The Intrusion Angle variable did not have a significant overall effect on the response variable, however, there was a statistically significant effect at a specific variable level (sideswipe, rear end) in the lost time regression model. This variable showed that while rear end intrusions are the most frequent, sideswipe, and head on intrusions also predict a high risk of serious injury.

Most injuries were minor to moderate, with an ISS of ten or less, and according to the graphics, the nature of most reported injuries were soreness, sprain/strain, or bruising. The most likely explanation of the high number of minor injuries is reported activity at the time of the accident. By further division of the Activity Type, it was found that all activities could be categorized as ‘driving’ or ‘on foot’. Since ‘driving’ was the most reported activity, this is most likely the reason for the high number of minor injuries. In the statistical analysis, activity type was found to have a s significant effect on work zone injury severity. The reason for this is that activities performed from a vehicle have the benefit of positive protection of the vehicle often in the form of a truck mounted attenuator (TMA).

All of the parameters analyzed are useful in understanding how work zone parameters effect injury. This information is essential for evaluation of work zone sites, in preparation for developing a safety plan.

The most effective way to use the information developed here for work zone evaluation is to use a numeric metric, or ‘Risk Index’. A metric will benefit work zone planning, as it presents an objective way to evaluate the risk of injury at a work site. The metric should take into account all work zone parameters found to have a statistical effect on injury severity. These parameters include the VMT, time of day, activity type, location and duration of the work zone. Each parameter is given a value, and using a metric formulation, the effect of all parameters are combined. The work zone with the highest Risk Index represents the work zone that has the highest risk of serious injury. The formulation for the Risk Index follows, where the parameter name would be replaced by a corresponding Coefficient:

Risk Index = (Duration) +(No. of Workers)(On Foot)+
(No. of Workers)(Driving)+(VMT)+
(No. of Hours)(Rush Hour)+
(No. of Hours)(Nonpeak Hours)+(Location)

In order to come up with a metric containing all five variables, a new regression model was created. Two possible models were created, a logistic model comparing the categorical AIS response variable with the five selected explanatory variables, and a Poisson regression model with the response (or count) variable being ISS. The two models were created using SAS. The logistic model experience quasi-complete separation of the data, which was most likely a result of the limited data points at higher AIS values. However, the Poisson model, typically used for data in which high count or frequency is a rare event, converged. The Goodness of Fit and Type 1 and 3 analysis results are shown in Figure 2.29. The calculated odds ratio values corresponding to each variable level were used as the Coefficient values for each variable level.

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	285	1226.5092	4.3035
Scaled Deviance	285	285.0000	1.0000
Pearson Chi-Square	285	2277.1826	7.9901
Scaled Pearson X2	285	529.1416	1.8566
Log Likelihood		66.9362	

LR Statistics For Type 1 Analysis

Source	Deviance	Num DF	Den DF	F Value	Pr > F	Chi-Square	Pr > ChiSq
Intercept	1781.1539						
VMT	1772.0631	2	285	1.06	0.3491	2.11	0.3478
Time Code	1655.2323	1	285	27.15	<.0001	27.15	<.0001
Activity Type	1316.9006	1	285	78.62	<.0001	78.62	<.0001
Location	1277.8265	5	285	1.82	0.1097	9.08	0.1059
Duration	1226.5092	2	285	5.96	0.0029	11.92	0.0026

LR Statistics For Type 3 Analysis

Source	Num DF	Den DF	F Value	Pr > F	Chi-Square	Pr > ChiSq
VMT	2	285	2.90	0.0569	5.79	0.0553
Time Code	1	285	23.90	<.0001	23.90	<.0001
Activity Type	1	285	74.29	<.0001	74.29	<.0001
Location of Accident	5	285	1.51	0.1860	7.56	0.1822
Duration	2	285	5.96	0.0029	11.92	0.0026

Figure 2.29: SAS output for the Poisson regression Risk Index model.

Parameter		Coefficient	Weight
VMT	3 (High)	1.2306	0.0267
	2 (Medium)	0.7312	
	1 (Low)	1.0000	
Time Code	1 (Peak/Rush Hour)	2.7643	0.2202
	0 (Non-peak Hour)	1.0000	
Activity Type	On Foot	3.6194	0.6843
	Driving	1.0000	
Location	Freeway/Highway	1.3024	0.0139
	Shoulder Closure	0.7996	
	City Street	0.7671	
	Freeway Ramp	0.7197	
	Freeway Lane Closure	0.8448	
	Moving Lane Closure	1.0000	
Duration	Mobile	1.4948	0.0549
	Short Duration	0.7990	
	Short-term Stationary	1.0000	

Table 2.19: Coefficient and weight values for the Risk Index.

It was important to keep the variable effects in perspective, therefore, a weight factor was used, specific to the significance of each variable in the Poisson regression model. The F-value, output in the 'LR Statistics for Type 3 Analysis', was used, as it is a measure of the significance of the effect by testing the additional contribution of each variable in the model. The F-values were normalized, such that each value represented a percentage of the total weight of the index. This was done by summing all F-values, then dividing each individual F-value by the total sum. The weight factors, and corresponding Coefficients are shown in Table 2.19. The Risk Index, defined previously, is rewritten as:

$$RiskIndex = C_{VMT}W_{VMT} + (\#Hours)C_{Time_0} + (\#Hours)C_{Time_1}W_{Time} + (\#Workers)C_{Activity_0} + (\#W\ workers)C_{Activity_1}W_{Activity} + C_{Location}W_{Location} + C_{Duration}W_{Duration} \quad (2.1)$$

Where C_{VMT} represents the Coefficient for the VMT variable, and W_{VMT} represents the weight for the same variable. When evaluating a potential work zone, there will be one Coefficient selected corresponding to the appropriate variable level for the VMT, Location, and Duration variables. The Time Code and Activity Type variables are treated differently because one work zone may span both levels of the variable. For example, an eight hour work zone may operate four hours during peak travel time (C_{Time_1}=2.7643) and four hours during non-peak ours (C_{Time_0}=1.0000).

The interpretation of the Coefficients follows the interpretation of odds ratios for the Poisson regression. For example, looking again at the Coefficients for time of day, for activity during peak/rush hours, C_{Time_1}=2.7643, compared to the Coefficient for non-peak activity, C_{Time_0}= 1.000. This Coefficient system agrees with the interpretation of the regression model: the predicted severity of an injury obtained in work during rush hour is predicted be 2.7643 times the expected injury severity for work being done during non-peak hours.

The developed Risk Index is an objective, and scientifically based method capable of measuring and comparing work zone risk. The index should not be used to determine if the level of risk is acceptable, it should only be used as a comparative tool. Further research should be done, documenting the calculated level of risk and the resulting injuries that occur in the work zone. After sufficient data are collected, the data would be analyzed to determine a threshold risk value based on calculated risk and actual accidents/injuries that take place in the work zone.

2.6 Conclusion

Generally, the injury analysis performed is useful to understand the trends and patterns in work zone injuries. By gaining a better understanding of the injury patterns and work zone parameters that are likely to increase injury risk, governing bodies can be more proactive in work zone safety planning.

The logistic regression analysis of the California work zone injury data determined that the type of activity being performed, the duration of the work zone, and the VMT rating of the area all affected the probability of a worker receiving a non-minor injury. Predicting the mean modified and lost time required after a work zone injury is another way to illustrate injury severity and its effect on the efficiency of the agency. Each modified or lost day corresponds to lost productivity, increased time delay to the traveling public, and ultimately cost to the agency. The statistical analysis found that all factors considered affected the expected modified or lost time due to an injury, although only a few had a statistically significant effect over all, including the VMT of the surrounding area, the location, activities being performed and duration of the work zone, the time of day, and the body region injured.

Combining the results, the development of a Risk Index which included the effects of Duration, Activity Type, VMT, Time of Day, and Location, provides planning agencies with a tool that will aid in work zone safety planning based on the knowledge gained in the injury analysis.

Chapter 3

Cost Benefit Analysis and Risk Assessment

3.1 Cost Benefit Analysis

Cost benefit analysis is a policy or project assessment method that quantities, in monetary terms, the value of all policy consequences to all members of society, [5]. The net social benefits measure the value of the project or policy, which are found by taking the benefits and subtracting from them the costs. It is important to note that the costs and benefits are considered for society as a whole, not just the specific people or groups involved. For this reason, a cost benefit analysis is commonly called a social cost benefit analysis. A basic cost benefit analysis, which may be applied to policies, programs, projects, regulations, demonstrations, and other government interventions, consists of nine basic steps, according to Boardman, et al., [5]:

1. Specify the set of alternative projects.
2. Decide whose benefits and costs count.
3. Catalogue the impacts and select measurement indicators, or units.
4. Predict the impacts quantitatively over the life of the project.
5. Monetize (attach dollar values to) all impacts.
6. Discount benefits and costs to obtain present values.
7. Compute the net present value of each alternative.
8. Perform sensitivity analysis.
9. Make a recommendation based on the net present value and sensitivity analysis.

In this research, an alternative highway work zone set-up, or protection layout was evaluated, namely, use of the Balsi Beam. Therefore, a Balsi Beam protected work zone would serve as the alternate 'project' to be evaluated in the first phase of the cost benefit analysis. The alternative project should be compared to the status quo, which is the traditional work zone set-up (coned-off lane closures). Step 2 touches on the idea that a decision may have different effects on different groups of people. For example, should the analysis be performed from the global, national, state, or local perspective. Because California work zone injury data were used to form estimates for one particular beneficial impact, the entire evaluation should be performed at the state level. Steps 3, 4 and 5 require the collection of impacts of the projects, and placing a monetary value on each cost or benefit. The term 'impact' refers to both inputs, or required resources, and outputs. There are many potential costs and benefits of highly mobile barrier use, including purchase price of the barrier, the equipment necessary to use the barrier, personnel training, time of work zone set-up and work completion, delay time to the traveling public, and injuries averted. The final benefit of highly mobile barriers, injuries averted, will be discussed in more detail in section 3.2, during which a monetary value will be determined for the impact.

The final steps in a cost benefit analysis, as listed, will not be performed in this research. However, it is important to understand the procedure. It is necessary to discount the benefits and costs to obtain present values (step 6) because of society's preference to consume now, rather than later. After the net present value of each cost and benefit is calculated, the net present value of each alternative is calculated by computing the difference between the present value of the benefits and the present value of the costs. While the analyst will recommend the alternative with the largest possible net present value, a sensitivity analysis is important to evaluate any uncertainties in the predicted impacts and/or assigned monetary valuations. Upon completion of the sensitivity analysis, the analyst can make a stronger recommendation.

It is important to note that the result of a cost benefit analysis is only a recommendation, and not a decision. The calculated net present values are merely expected values. The sensitivity analysis may suggest that the recommended alternative may not be the best choice in all situations.

3.2 Injury Cost Model

There are many costs and benefits associated with use of highly mobile barriers, many of which are beyond the scope of this research. However, as mentioned previously, California work zone injury data were used to estimate the benefits of injuries or fatalities averted.

Development of an injury cost model is an important step in the cost benefit analysis of highly mobile barriers. One has to consider both direct economic costs as well as the total economic costs. These costs cover direct losses and economic costs of motor vehicle crashes as well as the economic value society places on the human life and pain and suffering.

The method used here to determine the cost of an injury or fatality averted is to use accident costs. Accident costs are used in economic analyses for choosing among alternate improvements to existing road, street, and highway systems. Or, when dealing with highway safety, accident costs may be used for determining allocation of highway safety resources among programs, evaluating proposed safety regulations, or to convince policy makers that safety programs are beneficial [29].

Three measures of accident costs are commonly used to account for the costs of accidents in different ways,[29]. The first, and the method used in this research, is referred to as the *Comprehensive Cost*, which measures motor vehicle accident costs that include the effects of injuries or fatality on a person's entire life. This measure includes all cost components and places a dollar values on each component. There are eleven components that constitute the comprehensive cost. These components are: property damage, lost earnings, lost household production, medical costs, emergency services, travel delay, vocational rehabilitation, workplace costs, administrative, legal, and pain and lost quality of life. A second measure, *Years Lost Plus Direct Costs* includes the same costs as the comprehensive cost method, however, it replaces lost earnings, lost household production, and pain and lost quality of life with the non-monetary measure of lost years. The remaining components, termed 'direct costs', are also included. Finally, the *Human Capital Cost* measure included all comprehensive cost components with the exception of pain and lost quality of life.

In 1993, the U.S. Department of Transportation adopted a guidance entitled *Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analysis*, in which a procedure was established for determining and using accident costs to estimate the value of a statistical life

(VSL), [28]. The document stated that the benefit of preventing a fatality is measured by the VSL, which is defined as the value of improvements in safety that result in a reduction by one in the expected number of fatalities. The VSL, put forth by the U.S. Department of Transportation, is to be used in all departmental economic analyses when the reduction of fatalities or injuries is a benefit. While this estimate is accepted, it is noted that analysts using the VSL must recognize the subjective qualities of the estimate.

The society's valuation of safer transportation is the basis of the VSL, and includes individual travelers' own willingness to pay to reduce the risk of accidental death and injury they face in using the transportation system. Willingness to pay is based on the observed willingness to pay modest amounts for a small reduction in risk. For example, if 10 million passengers on an already safe mode of transportation were willing to pay $0.20 extra in their fare to reduce the risk of accidental death per trip by 0.0000001, over the 10 million trips, $2 million would be collected, and one less life would be lost. The willingness to pay would be $2 million per life, although no one would have actually expressed willingness to pay that amount to save his/her life, [28].

Based on further research, the U.S. DOT published a revised document, in which the VSL was updated based on published research and the procedures of other government agencies, [31]. The new VSL value of $5.8 million was set forth in 2008 as an appropriate reflection of research results.

If fatality reduction is a benefit in a proposal, expected reduction in non-fatal injury is most likely another benefit, as injuries are far more common than fatalities. Determining a willingness to pay value for injury averted is difficult due to the potential injury severity range. In the Departmental guidance, [28], a method to determine the 'fatality equivalent' was presented, based on the research by Miller et al., [17], who, rather than determining a willingness to pay estimate, defined a set of Coefficients that can be used to convert VSL into injury estimates. Table 3.1 lists the Coefficients used to calculate the equivalent VSL for injury categories defined by the AIS.

MAIS Level	Severity	Fraction of VSL
MAIS 1	Minor	0.0020
MAIS 2	Moderate	0.0155
MAIS 3	Serious	0.0575
MAIS 4	Severe	0.1875
MAIS 5	Critical	0.7625
MAIS 6	Fatal	1.0000

Table 3.1: Coefficients used to calculate the 'fatality equivalent', or fraction of VSL for non-fatal injuries. (MAIS: Maximum Abbreviated Injury Score, VSL: Value of a Statistical Life)

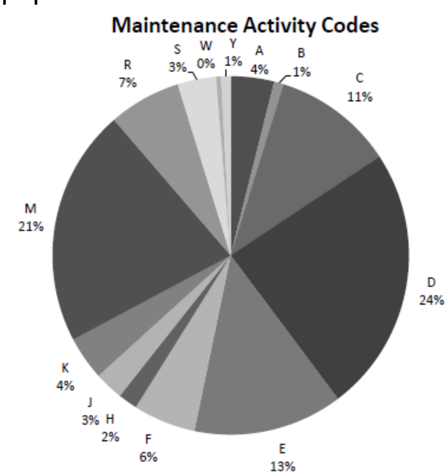
Using the table, and the established VSL value, an injury cost model can be developed and added to the cost benefit analysis. The injury cost model is only one of many social costs and benefit analyzed in a complete cost benefit model.

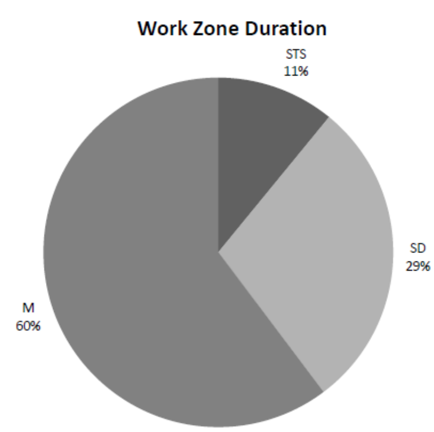
3.2.1 Injury Cost Estimates

Using the California highway work zone injury data and the guidance set forth by the U.S. Department of Transportation, [31], an injury cost model was developed. Accident/injury costs were calculated for work zone intrusion accidents where a worker injury was reported. In all, there were 299 work zone intrusion accidents evaluated over the ten year period of interest. Figure 3.1 shows the reported maintenance activity, work zone duration, and injury severity (rated by AIS) of the most severe injury for these reported accidents. (Maintenance activity codes are defined in Table 2.11.)

Using the Coefficient equivalents defined in Table 3.1, and the injury severity data represented in Figure 3.1, a total cost of injury over the 10 year period was calculated to be $3.167 million for minor injuries, $1.798 million for moderate injuries, $0.334 million for serious injuries, and $29 million for fatalities. The total cost is found to be $34.293 million, which can be estimated to a yearly average of $3.43 million. (These results are shown in the third column (Total Cost) of Table 3.3.)

Using work zone maintenance and duration information, [26], and knowledge of barrier specifications and uses, Table 3.2 was constructed showing various work zone activities and their applicability for highly mobile barrier protection. (There are many other maintenance activities that may be protected by highly mobile barriers, however, the list presented in Table 3.2, only addresses those maintenance activities present in the data.) Determination of highly mobile barrier protection was based on the best possible work zone situations, considering maintenance activity spatial requirements, duration, and equipment needs.





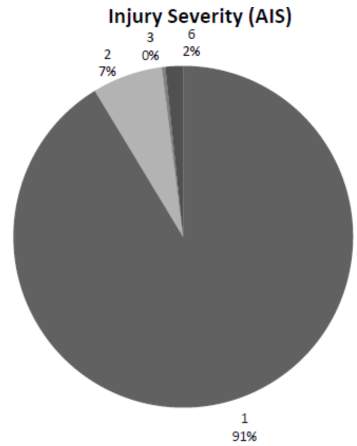


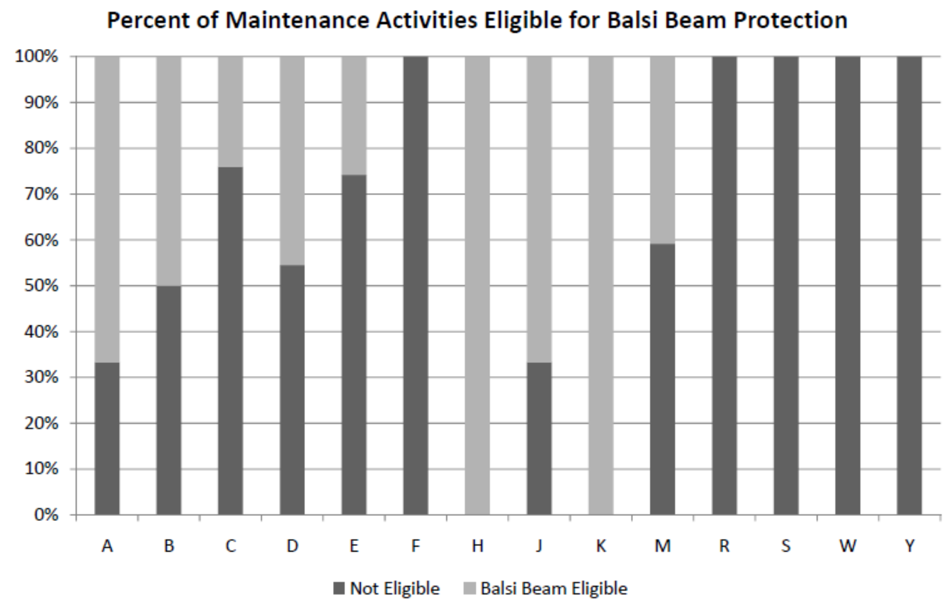
Figure 3.1: Breakdown of maintenance activity, work zone duration and injury severity (AIS) reported during work zone intrusion accidents in a 10 year period in California.(STS: Short-term Stationary, SD: Short Duration, M: Mobile)

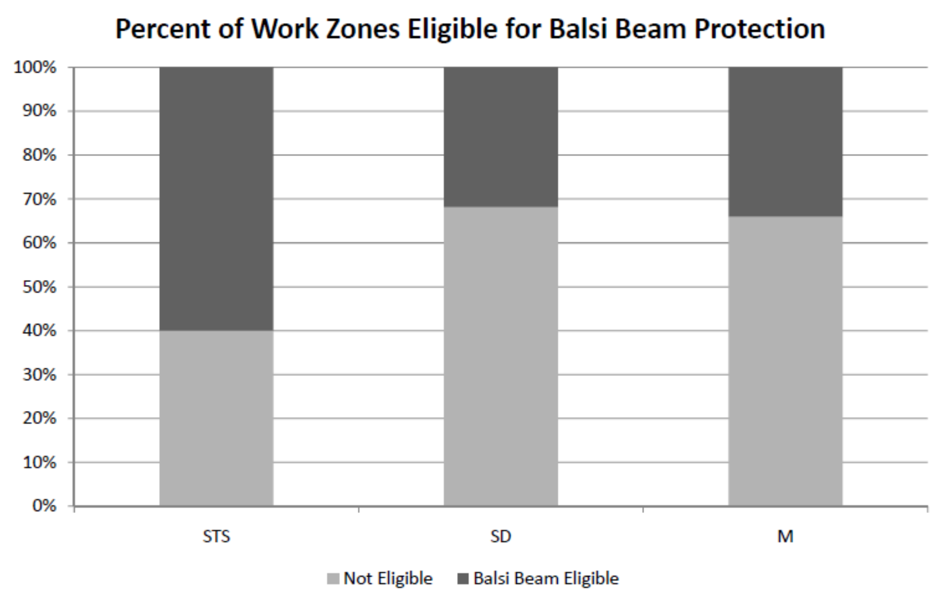
Maintenance Activities	Duration	BB Eligible
Bridge Maintenance	STS	X
Guardrail Repair	STS	X
Culvert/ Drain Work	SD	X
Lighting Work	SD	X
Sign Work	SD	X
Signal Work	SD	X
Concrete Slab Replacement	STS	X
Asphalt Milling	M	
Level-up Activities	M	
Joint Repair/ Crack Sealing	M	X
Sealcoat/ Asphalt Overlay	M	
Pothole Patching	SD	X
Raised Pavement Marker Work	M	X
Short-line Striping	SD	X
Pavement Striping	M	
Litter Pickup	M	X
On-road Equipment Repairs	SD	X
Landscape Work	STS	X
Snow/ Ice Control	M	
Storm Maintenance	M	

Table 3.2: Summary of maintenance activities eligible for highly mobile barrier protection. (BB: Balsi Beam, STS: Short-term Stationary, SD: Short Duration, M: Mobile)

When considering Balsi Beam deployment, 83, approximately 28% of all work zone intrusion accidents, occurred in work zones that were eligible for Balsi Beam protection, (or 7.5% of all work zone accidents reported). Figure 3.2 shows the percent of maintenance activities, duration and injury severity of work zones appropriate for Balsi Beam deployment. When evaluating the corresponding accident costs, Table 3.3 shows the difference in costs between all work zone intrusion accidents (Total Costs) and work zone intrusion accidents occurring in work zones suitable for highly mobile barrier protection (Averted Costs).

These costs can be used as benefits in the cost benefit analysis in terms of fatalities and injuries averted if a particular barrier is used. For example, one year of Balsi Beam protection at eligible work zone sites is expected to save 0.3 lives, and avoid 1 moderate injury and 7 minor injuries. These avoided injuries amount to a monetary savings of $1.91 million. Caution must be taken when dealing with future costs and benefits, and the appropriate discount must be considered [5]. For this reason, the net benefits of one year of highly mobile barrier protection are examined here.





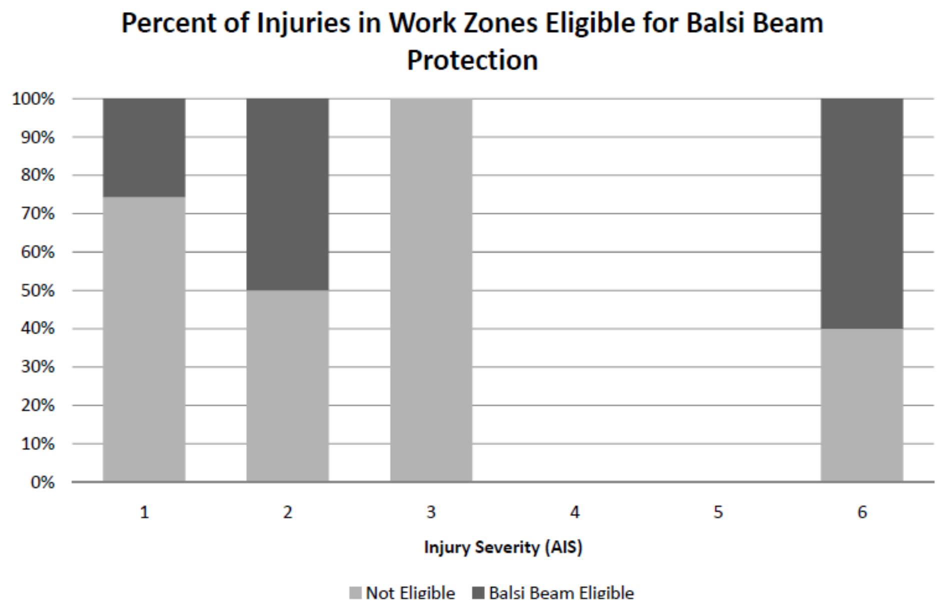


Figure 3.2: Percent of work zones where intrusion accidents were reported eligible for Balsi Beam protection, by maintenance activity, duration, and injury severity.

Injury Severity (MAIS)	Injury Cost (Millions)	Total Costs (Millions)	Averted Costs (Millions)
1	0.0116	3.167	0.812
2	0.0899	1.798	0.899
3	0.3335	0.334	0
4	1.0875	0	0
5	4.4225	0	0
6	5.8000	29.0	17.4
Total		34.298	19.111
Expected Yearly Average		3.430	1.911

Table 3.3: Injury cost model comparing all work zone injury costs (Total) to the expected averted costs in work zones eligible for Balsi Beam deployment (Averted) over the 10 year period of interest.

As previously mentioned, additional impacts, or effects, must be considered to perform a thorough cost benefit analysis. Additional impacts, including barrier deployment time and congestion costs are further examined in the next section.

3.3 Operational Cost Estimates

In addition to the costs and benefits associated with averted injuries and fatalities, other impacts to consider include material and equipment costs, personnel training, time required to set-up and take-down the positive protection, and congestion costs. The costs associated with material and equipment, and personnel training, are outside the scope of this research. However, time of exposure and the effects on congestion may potentially have an effect on the risk of serious injury to the worker. These two elements are further discussed.

3.3.1 Exposure Time

The time necessary to deploy positive protection is important, as it may be the deciding factor in the efficiency and use of a highly mobile barrier. A typical maintenance work zone lane closure, consisting of signage and cones, takes 15–20 minutes to set up. While this time depends on many factors, such as work zone length, traffic volume, and speed limit, the procedure exposes the workers to risk of injury for the entire duration of the work zone maintenance task, in addition to the time required to set up the work zone. Table 3.4 shows the estimated time required for work zone positive protection (Balsi Beam) deployment according to product information and demonstrations. In contrast to traditional work zone delineation, use of positive protection limits the exposure, or risk of injury of the worker to only the time required to deploy the barrier.

The exposure during barrier deployment has not been quantified by means of cost necessary for the cost benefit analysis. However, review of Table 3.4 shows that the Balsi Beam requires less time to deploy, thus reducing the amount of exposure workers experience during barrier deployment.

Barrier Type	Length of Protected Work Zone	Estimated Deployment Time
Balsi Beam	9 m (30 feet)	10 minutes
Typical Coned Lane Closure	–	15–20 minutes

Table 3.4: Approximate times of deployment for the Balsi Beam, compared with a typical lane closure.

3.3.2 Congestion and Delay

The effect on congestion and traffic delay has the potential to add large costs and benefits to a cost benefit analysis. The effect of a work zone on traffic flow will vary greatly depending on the time of day, traffic composition, and work zone location. However, assuming all are held constant, the additional time and space needed to set up the work zone can have an effect on costs. These costs are addressed using a Road User Cost (RUC) calculation. The RUC is defined as the estimated daily cost to the traveling public resulting from road work being performed. The cost primarily considers lost time caused by any number of conditions including

- Reduced roadway capacity that slows traffic speed and increases travel time,
- Delays in the opening of a new and/or improved facility that prevents users from gaining travel, and

- Detours that add to travel time.

RUC calculation procedures were defined by the Division of Research and Innovation (DRI) at Caltrans and the State of New Jersey Department of Transportation [10, 24], based on NCHRP Report 133: Procedures for Estimating Highway User Costs, Air Pollution, and Noise Effects, [11]. The calculations consider cost components associated with unrestricted flow, (free flow), queue, (forced flow), and detour, (circuitry). (The NJ Department of Transportation also incorporates crash costs in their calculations.)

Following a template developed by Caltrans, the total RUC is found by adding together the calculated RUC associated with the three listed conditions.

RUC_{Total} = *Sum of all RUCs*

= $RUC_{WZ} + RUC_{Delay} + RUC_{Detour}$

where,

RUC_{WZ} = *Work Zone reduced speed delay costs*

RUC_{Delay} = *Queue delay costs (Stop and Go) +*
Queue delay vehicle operation cost (VOC)

RUC_{Detour} = *Detour delay (due to added length/time) +*
Detour VOC (due to added length/time)

Caltrans (DRI) developed a 'Short Form Calculation Tool', using Microsoft Excel, which includes an Input Module and an Output Module. The Input Module contains specified fields where the user may change cost and capacity estimations for the specific roadway and work site. The required input fields, as shown in Figure 3.3, are:

1. Project description (county, route number, post mile, direction, etc.)
2. Work zone traffic information (24-hour traffic and road conditions, traffic composition, total lanes)
3. Work zone and vehicle speed information (work zone length, unrestricted and work zone speed of vehicles)
4. Detour and vehicle speed information (travel length with and without detour, speed on detour)

The second input field, 'Work zone traffic information', was used to address both the time and spatial needs of the highly mobile barrier. The additional lane needs to set up the work zone are accounted for by adjusting the number of free, or open travel lanes.

Also shown in Figure 3.3, are the outputs calculated by the RUC Module:

- Total vehicles that travel queue
- Total vehicles that travel work zone
- Total vehicles that travel detour
- Daily Road User Cost (RUC) ($/day)
- Calculated Road User Cost (CRUC) ($/day)
- Total Road User Cost (RUC_{Total})

Road User Cost (RUC) Model

Data Input Module

Instruction: The input data required are highlighted.

1) **Project Description:**

County:	DEMO	PM:	6.56-7.09	Chart No.:	1
Route:	0	EA:		Direction:	SB
Working Days:	1	By:		Date:	mm/dd/yy

2) **Work Zone Traffic Information:**

24 Hour Traffic and Road Condition		
Time Period (hour)	Vehicle Demand (vph)	Lanes Open (#)
0-1	736	3
1-2	488	3
2-3	335	3
3-4	421	3
4-5	621	3
5-6	2,057	3
6-7	4,385	3
7-8	5,480	3
8-9	5,531	3
9-10	5,619	2
10-11	5,294	2
11-12	5,353	2
12-13	5,418	2
13-14	5,479	2
14-15	5,707	3
15-16	5,990	3
16-17	5,299	3
17-18	4,830	3
18-19	4,796	3
19-20	3,971	3
20-21	3,223	3
21-22	2,561	3
22-23	1,775	3
23-24	1,207	3

Percent Trucks:	15.10%
Total Lanes:	3

Capacity Assumptions	
Lane Open (# Lns total)	Capacity (vph)
1	1,500
2	3,200
3	5,100
4	8,000
5	
6	

3) **Work Zone And Vehicles' Speeds:**

Work Zone Length (mile)	2	
	Car	Truck
Unrestricted Speed (mph)	65	55
Work Zone Speed (mph)	65	55

One-way Traffic Control:

Waiting Time (hr/veh)	0

4) **Detour And Vehicles' Speeds:**

Travel Length without Detour (mile)	0	
Travel Length with Detour (mile)	0	
	Car	Truck
Speed on Detour (mph)	40	35

RUC Output Module

Total Vehicles that Travel Queue:	61,973
Total Vehicles that Travel Work Zone:	16,000
Total Vehicles that Travel Detour:	0

Daily Road User Cost ($/d):	776,786
Calculated Road User Cost (CRUC) ($/d):	388,393
Total Road User Cost ($):	388,393

USER COST ASSUMPTIONS

Cost Rate ($/veh-hr)		Autos	9.000
		Trucks	24.000
Idling Cost ($/veh-hr)		Autos	0.680
		Trucks	0.780
Vehicle Operating Cost ($/mile):			
	Speed	Autos	Trucks
	5	0.374	0.642
	10	0.306	0.493
	15	0.267	0.440
	20	0.240	0.421
	25	0.227	0.420
	30	0.215	0.438
	35	0.208	0.464
	40	0.204	0.498
	45	0.203	0.540
	50	0.200	0.588
	55	0.204	0.648
	60	0.208	0.715
	65	0.214	0.790

Note:

- This model may be used to estimate road user costs due to reduced work zone speed, queue delay or detour delay.
- Recurrent delay (i.e. queue delay during rush hours) is excluded in the road user cost.
- The average queue speed of trucks is assumed to be same as that of cars, which is under LOS-F and determined according to NCHRP 133 (1972).
- The roadway capacity per lane under normal condition or work zone condition can be adjusted accordingly.
- For a 2 lane one-way traffic control condition, vehicle demand should be the sum of two directional traffic volume. The total number of lanes should be 2. The work zone speed could be 10-15 mph.

Figure 3.3: Sample of the RUC Short Form Calculation Tool created by DRI.

The RUC tool enables the effect of different protection methods to be more fully evaluated. Using the RUC, the effect on traffic delay can be calculated and quantified. The RUC is another tool used by Departments of Transportation to determine the effectiveness of various alternatives in work zone planning, including detours, temporary roadway or shoulder construction, off-peak hour day work, and night work.

3.3.3 Sample RUC Calculations

To demonstrate the use of the RUC as a tool for work zone protection methods, two sample work zones were evaluated. Assuming that both protection methods (Balsi Beam deployment versus traditional lane closure) provide equal protection in the two ideal situations, spatial needs and deployment time requirements were addressed to calculate an estimated CRUC for two work zones. Table 3.5 lists the spatial and time requirements for each protection method in the two example work zones.

Time Period (hour)	Number of Open Lanes			
	WZA:BB	WZA:Cones	WZB:BB	WZB:Cones
8-9	2	2	2.83	2.67
9-10	1.83	1.67	2	2
10-11	1	1	2	2
11-12	1	1	2	2
12-13	1	1	2	2
13-14	1	1	2	2
14-15	2	1.67	3	2.67
15-15	2	2	3	3

Table 3.5: Portion of the '24 Hour Traffic & Road Conditions' table under the Work Zone Traffic Information field in Figure 3.3. (WZA: Work Zone A, WZB: Work Zone B, BB: Balsi Beam, Cones: Traditional Coned Lane Closure)

Work Zone A (WZA) occurred on a two mile stretch in the southbound direction of a four lane roadway. If a traditional lane closure were utilized, one travel lane would be available, and one closed for a four hour period from 10:00 to 14:00. Spatial needs for barrier deployment or lane closure are considered, as well as the time for deployment, by adjusting the number of open lanes. The Balsi Beam does not require additional space, however, an additional 10 minutes are necessary for deployment. In comparison, the estimate of 20 minutes was used to account for the time needed to deploy a full lane closure, as shown in Table 3.5. To determine the number of open lanes the deployment time was combined with the spatial needs to produce a fraction. For example, the Balsi Beam requires about 10 minutes to fully deploy. Therefore, from 9–10, 1.83 lanes will be available (2 open lanes for 50 minutes, 1 open lane for the remaining 10 minutes). Using the 20 minute estimate for full (traditional) lane closure, the number of open lanes becomes 1.67 for the hours preceding and following planned maintenance.

Work Zone B (WZB) is modeled after a three mile work zone on the northbound side of a six lane highway. The traffic composition of WZB consists of 5.00% trucks (compared to 15.10% trucks at WZA). Both work zones reported the same free flow and work zone speed limits, however, due to the larger number of lanes available, WZB experienced a higher vehicle demand. Both Work Zone A and B were analyses performed for work zone planning. The vehicle demand estimates, and traffic composition data were based on data from the PeMS database, [1].

Work Zone A

	Balsi Beam	Cones
Total Vehicles that Travel Queue	24,116	26,122
Total Vehicles that Travel Work Zone	7,500	9,000
Total Vehicle that Travel Detour	0	0
Daily RUC ($/Day)	193,539	263,374
CRUC ($/Day)	96,770	131,687

Work Zone B

	Balsi Beam	Cones
Total Vehicles that Travel Queue	67,662	68,252
Total Vehicles that Travel Work Zone	19,200	22,400
Total Vehicle that Travel Detour	0	0
Daily RUC ($/Day)	883,984	1,014,179
CRUC ($/Day)	441,992	507,090

Table 3.6: RUC estimates for two sample work zones, using the RUC Tool developed by Caltrans [10].

Work Zone A

Barrier Type	CRUC ($/Day)	% Difference
Balsi Beam	96,770	–
Cones	131,687	26.5

Work Zone B

Barrier Type	CRUC ($/Day)	% Difference
Balsi Beam	441,992	–
Cones	507,090	12.8

Table 3.7: Percent difference in CRUC for different work zone protection methods.

Using the RUC Tool, shown in Figure 3.3, estimated vehicle travel totals and daily RUCs were calculated. The results are shown in Table 3.6. Table 3.7 summarizes the CRUC and the percent difference (increase) in the CRUC comparing Balsi Beam usage to a traditional lane closure using cones. In these two demonstrations of RUC, the traffic volume can be seen to have a large effect on the RUC. Higher vehicle demand leads to a higher number of vehicles traveling the queue and work zone, which increases user cost. The results shown in Table 3.6 and Table 3.7 show how deployment and spatial requirements affect the RUC estimate.

3.4 Combined Injury and Operational Cost Benefit Analysis

The RUC estimates, which represent two areas of the operational cost benefit analysis (deployment time and congestion effects) can be combined with the injury cost benefit analysis results to present a more thorough evaluation of the two different work zone protection methods.

Injury Severity (MAIS)	Total Cost (Millions)	Balsi Beam Averted Costs (Millions)
1	3.167	0.812
2	1.798	0.899
3	0.334	0
4	0	0
5	0	0
6	29.0	17.4
Total	34.298	19.111
Expected Yearly Average	3.430	1.911

Table 3.8: Injury cost model showing expected averted costs for work zones eligible for Balsi Beam protection compared to the total cost of injury without positive protection.

Recall the results of the injury cost model, which calculated the expected averted costs for work zones eligible for positive protection, based on the California injury data (reprinted in Table 3.8). If the 'Total Cost' column represents the expected injury cost in a traditional lane closure, then the 'Averted Cost' column reports the cost savings of highly mobile barrier use. Rewriting the table, as expected cost savings, Table 3.9 represents the data presented in Table 3.8 in a different manner.

Injury Cost Component ($)

Injury Severity (MAIS)	Traditional Lane Closure	Balsi Beam Protection
1	0	812,000
2	0	899,000
3	0	0
4	0	0
5	0	0
6	0	17,400,000
10 Year Total	0	19,111,000
Yearly Average	0	1,911,000
Operational Cost Component ($/Day)		
Work Zone A	131,687	96,770
Work Zone B	507,060	441,992

Table 3.9: Estimated savings based on injury data and RUC cost calculations.

The second portion of Table 3.9 shows some operational costs for highly mobile barrier use, based on deployment time and congestion effects. Subtracting the estimated operational costs from the expected benefits of averted injuries would yield a better estimate of a cost benefit analysis result. (It is important to remember that there are additional elements not evaluated here, that are necessary to consider for a complete cost benefit analysis.) Obviously, barrier used depends greatly on the planned maintenance activity. However, the results shown here represent a sample analysis and introduce potential cost patterns.

3.5 Risk Assessment Model

A risk assessment is a means of providing quantitative and qualitative measures of the potential severity and probability of injury or damage in order to guide a decision, [7]. In other words, a risk assessment provides a scientific basis for decision making. As a way to aid in decision making in relation to work zone safety planning, a risk assessment was initiated, focusing on Balsi Beam deployment as a means to reduce the risk on highway short-term and temporary work zones.
The typical steps in risk assessment are summarized below:

1. Identify all potential risks and hazards.
2. Determine the probability of occurrence by estimating the likelihood of injury or adverse effects from the risk and the expected frequency of exposure.

3. Identify, evaluate, and implement solutions that will mitigate or reduce risks, using the cost benefit analysis as an aid in solution evaluation.
4. Review and document the risk assessment results on a regular basis and update when necessary.

The initial steps of risk assessment were developed in this research. Identification of risk was established and presented previously in this report, where the trends in work zone accidents producing worker injuries were evaluated. The likelihood of injury or probability of occurrence was completed using the California work zone injury data to produce the Risk Index, Eq. (2.1). The Risk Index is a metric useful in measuring the risk of injury in highway maintenance work zones. A solution to mitigate risk, in the form of the Balsi Beam was presented. Social benefit costs were derived for the barriers in the injury cost models, and were presented for further use in the cost benefit analysis. The final steps in risk assessment that remain to be completed include selection and implementation of a risk mitigation device, and an iterative review of the risks following implementation of the highly mobile barriers in use.

Bibliography

[1] A COOPERATIVE EFFORT BETWEEN UC BERKELEY, CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS, AND CALTRANS, PEMS.EECS.BERKELEY.EDU. *Freeway Performance Measurement System (PeMS)*.

[2] ASSOCIATION FOR THE ADVANCEMENT OF AUTOMOTIVE MEDICINE. *Abbreviated Injury Scale 2005*. Barrington, IL, USA, 2007.

[3] BAKER, S. P., O'NEILL, B., HADDON, W., AND LONG, W. B. The injury severity score: A method for describing patients with multiple injuries and evaluating emergency care. *The Journal of Trauma 14*, 3 (March 1974), 187–196.

[4] BLINCOE, L. J. *The Economic Cost of Motor Vehicle Crashes, 1994*. National Highway Traffic Safety Administration, Washington, DC, July 1996.

[5] BOARDMAN, A. E., GREENBERG, D. H., VINING, A. R., AND WEIMER, D. L. *Cost-Benefit Analysis: Concepts and Practice*, second ed. Prentice Hall, 2001.

[6] BOHLIN, N. A statistical analysis of 28,000 accident cases with emphasis on occupant restraint value. *In Proceedings of the 11th STAPP Car Crash Conference (New York, 1967)*, pp. 299–308.

[7] BROWN, S. J., AND BROWN, T. J. Hazardous release protection: Code and standard considerations for pressure systems. *Process Safety Progress 14*, 4 (October 1995).

[8] CALIFORNIA DEPARTMENT OF TRANSPORTATION. *Highway Worker Safety*. www.dot.ca.gov/hq/paffairs/about/safety.htm, (Accessed July 2008).

[9] CALIFORNIA DEPARTMENT OF TRANSPORTATION. *California Strategic Highway Safety Implementation Plan: Safety Needs Action Plan for Challenge Area 14: Enhance Work Zone Safety*, August 2007. www.dot.ca.gov/hq/trafficops/survey/SHSP/challenge14.htm.

[10] CALIFORNIA DEPARTMENT OF TRANSPORTATION, TRAFFIC OPERATIONS. *Road User Costs and A+B Bidding*.

[11] CURRY, D., AND ANDERSON, D. *NCHRP Report 133: Procedures for Estimating Highway User Costs, Air Pollution, and Noise Effects*. Highway Research Board, National Research Council, Washington D.C, 1972.

[12] GENNARELLI, T. A., AND WODZIN, E. Ais 2005: A contemporary injury scale. *Injury, International Journal of the Care of the Injured 37* (2006), 1083–1091.

[13] GREENSPAN, L., MCLELLAN, B. A., AND GREIG, H. Abbreviated injury scale and injury severity score: A scoring chart. *The Journal of Trauma 25*, 1 (January 1985), 60–64.

[14] GRIFFIN III, L. *Analysis of the Benefits Derived from Certain Presently Existing Motor Vehicle Safety Devices, A Review of Literature*. University of North Carolina Highway Safety Research Center, 1973.

[15] KHATTAK, A. J., KHATTAK, A. J., AND COUNCIL, F. M. Analysis of injury and non-injury crashes in California work zones. *Transportation Research Board, 78th Annual Meeting* (January 1999). Paper No. 991438.

[16] KUTNER, M. H., NACHTSHEIM, C. J., NETER, J., AND LI, W. *Applied Linear Statistical Methods*, fifth ed. McGraw-Hill, 2005.

[17] MILLER, T. R., LUCHTER, S., AND BRINKMAN, C. P. Crash costs and safety investment. *Accid. Anal. and Prev. 21,* 4 (1989), 303–315.

[18] NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION. *Fatality Analysis Reporting System (FARS) Encyclopedia*. www-fars.nhtsa.dot.gov/Main/index.aspx, (Accessed July, 2008).

[19] QI, Y., SRINIVASAN, R., TENG, H., AND BAKER, R. F. *Frequency of work zone accidents on construction projects*. Final Report 55657-03-15, New York State Department of Transportation, US Department of Transportation, August 2005.

[20] RAGAVAN, A. J. How to use sas ®Global ® to fit multiple logistic regression models. In *SAS® Global Forum* (2008). Paper 369-2008.

[21] RYAN, G., AND BALDWIN, R. *In Depth Study of Seat Belt Accidents*. Monash University Medical School, 1972.

[22] SAS INSTITUTE INC. *SAS/STAT User's Guide*. v8doc.sas.com/sashtml/stat/index.htm.

[23] SCHROCK, S. D., ULLMAN, G. L., CATHRON, A. S., KRAUS, E., AND VOIGT, A. P. *An Analysis of Fatal Work Zone Crashes in Texas*. Texas Transportation Institute, College Station, Texas, October 2004. Report 0-4028-1.

[24] STATE OF NEW JERSEY DEPARTMENT OF TRANSPORATION. *Road User Cost Manual*, June 2001.

[25] STATES, J., BALCERAK, J., WILLIAMS, J., MORRIS, A., BABCOCK, W., POLVINO, R., RIGER, P., AND DAWLEY, R. Injury frequency and head restraint effectiveness in rear end impact accidents. In *Proceedings of the 16th STAPP Car Crash Conference* (New York, 1972), pp. 228–257.

[26] TEXAS TRANSPORATION INSTITUTE. *Development of Functional Requirements for a Highly-Mobile Barrier System to Protect Highway Workers: Final Report, July 2004*. Prepared for FHWA, U.S. Department of Transportation.

[27] ULLMAN, G. L., HOLICK, A. J., SCRIBA, T. A., AND TURNER, S. M. *Estimates of Work Zone Exposure on the National Highway System in 2001*. Transportation Research Board, Washington DC, 2004. Transportation Research Record No. 1877.

[28] U.S. DEPARTMENT OF TRANSPORTATION FEDERAL HIGHWAY ADMINISTRATION. *Treatment of the Economic Value of a Statistical Life in Departmental Analyses*, January 1993. Memo from the Office of the Secretary of Transportation.

[29] U.S. DEPARTMENT OF TRANSPORTATION FEDERAL HIGHWAY ADMINISTRATION. *Motor Vehicle Accident Costs: Technical Advisory*, October 1994. T 7570.2.

[30] U.S. DEPARTMENT OF TRANSPORTATION FEDERAL HIGHWAY ADMINISTRATION. *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2003 ed., November 2004.

[31] U.S. DEPARTMENT OF TRANSPORTATION FEDERAL HIGHWAY ADMINISTRATION. *Treatment of the Economic Value of a Statistical Life in Departmental Analyses, Update*, February 2008. Memo from the Office of the Secretary of Transportation.

[32] VIANO, D. C., AND AREPALLY, S. Assessing the safety performance of occupant restraint systems. In *Proceedings of the 34th Stapp Car Crash Conference* (November 1990). SAE Paper 902328.

[33] WANG, J., KNIPLING, R., AND BLINCOE, L. The dimensions of motor vehicle crash risk. *Journal of Transportation Statistics* (May 1999), 19–42.